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Volume 10 AUGUST, 1940 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 2, PP. 47–57, FIGS. 1–2, TABLES 1–4, AUGUST, 1940

TEXTURAL AND SHAPE VARIATION IN THE BEREA SANDSTONE OF OHIO

FRED FOREMAN AND HARRY L. THOMSEN
Oberlin College

INTRODUCTION

The samples for this paper on the textural and grain shape variation of the Berea sandstone were collected from some 16 localities along the line of outcrop in the state. Analyses from these data have been diagrammed and tabulated according to the methods now commonly used in sedimentary petrology.

It was the hope of the authors that a grid pattern of samples could be obtained from the well borings over the state, but such samples were not obtainable and the study was limited to the line of outcrop. Most of the histograms are the work of the junior author; the statistical measures used, the shape measurements and the conclusions are the work of the senior author.

In the study of roundness only quartz grains were used.

GEOLOGY

The Berea sandstone or Berea grit, as it was originally named by J. S. Newberry (1874), lies in the Waverly Group near the base of the Mississippian system. The formation takes its name from the village of Berea in Cuyahoga County, Ohio, where large quarries are located. The outcrop varies from 1 to 10 miles in width, extending from the Ohio-Pennsylvanian border in northeastern Ohio, westward to Erie County and then southward the length of the state, crossing the Ohio River some 20 miles west of the city of Portsmouth. The sandstone underlies all of the state to the east and south of the line of outcrop, an area of about 15,000 square miles (fig. 1).

A regional dip of 15 to 20 feet per mile toward the southeast causes the sandstone to lie some 800 feet below sea level in the southeastern part of the state. This regional dip and also the north-south line of outcrop are caused by the Cincinnati Arch.

Orton (1888) describes the sandstone as being of medium grain in northern Ohio and of fine grain in the central part of the state and southward, with shaly layers appearing in the extreme southern part. Across the Ohio River in Kentucky and Tennessee it becomes progressively more argillaceous. The maximum thickness is 225 feet in the Buckeye quarry at South Amherst and the average thickness in Ohio is 30 to 40 feet. The average thickness is less in the south than in the north. The upper surface of the Berea sandstone is fairly even but the lower surface is quite uneven. Drilling in the vicinity of South Amherst has shown that although the Berea ranges from 100 to 225 feet in the quarries, the stone may disappear entirely in the space between quarries, a distance in some places of no more than 200 to 300 yards. However, well records show that over most of the area the sandstone is continuous and much less variable in thickness than in the area of South Amherst, but even in the southern part of the state variations from 5 to 80 feet are found (Stout, 1916).

Where freshly quarried, the stone is usually massive, although weathering causes it to break into thin, flaggy layers. Cross-bedding and ripple marks are common along the entire line of outcrop. The color of the stone in the northern part is usually a very light gray to buff, although some beds show a yellow to red-brown speckling, and others have reddish brown streaks or bands along the

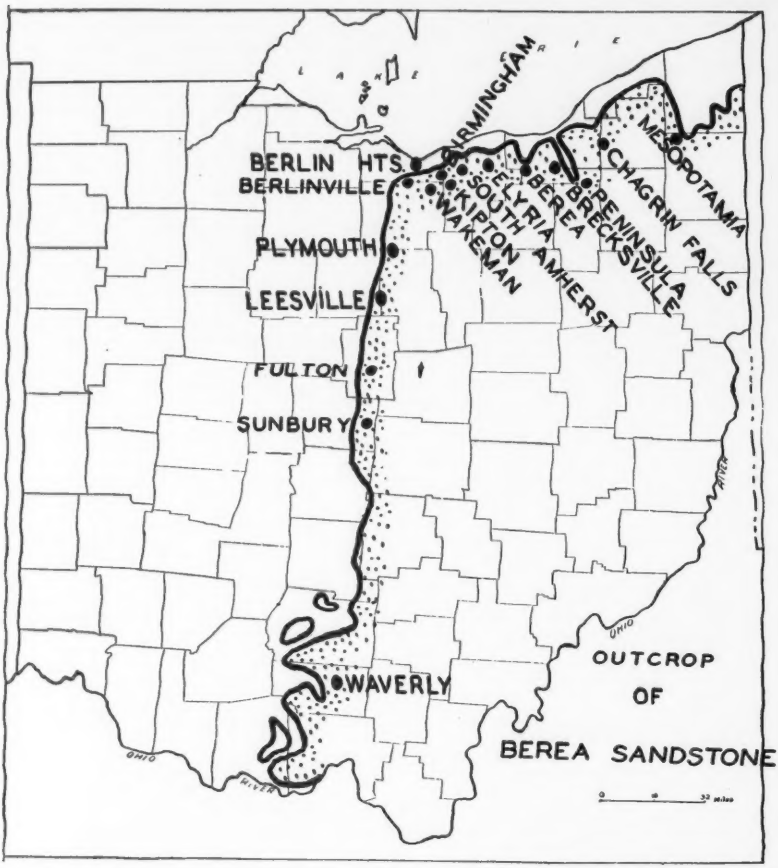

FIG. 1.—Map of Ohio showing the outcrop of the Berea sandstone and the location of samples.

bedding planes. Colors tend to deepen toward the south and locally become dark red-brown.

TEXTURAL VARIATION

Representative samples of the whole outcrop were taken from the top, middle, and bottom part at each locality (fig. 1). Because of the uniform character of the beds from top to bottom, it was found unnecessary to use data from the middle part except in the study of the very thick beds, such as are found in the quarries of Lorain and Erie Counties. In the two cases, Berea and Plymouth, it was not possible to obtain samples from the lower part.

The Berea sandstone is considerably harder and more difficult to disaggregate when dry than when it is fresh or "green" as the quarrymen express it. By storing the samples in water in sealed Mason

jars, it was found that they would keep fresh indefinitely. Disaggregation was effected by means of a porcelain mortar and wooden pestle, the pestle being tapped against the sample until all aggregates were separated. Frequent check by use of a microscope was necessary during the disaggregation to guard against aggregates and cracked grains. Such other methods of separating the grains, as boiling in dilute acid, boiling in a solution of sodium hyposulphite were tried, but the one above was the only one to completely disaggregate the particles.

About 100 grams of each of the samples were disaggregated and then quartered, and the one-quarter sieved in a mechanical shaker. Nine Tyler sieves from .991 to .061 mm. were used. The material passing the smallest sieve was further separated by the pipette method after Krumbein (1932), one gram of $NaCO_3$ being used as a deflocculant in each sample. Histograms were then made from the weight percentages in the usual manner following the Wentworth scale.

A number of different methods were tried for the recording of the data; the three methods given the most attention were: the method of equivalent grades after Baker (1926), the quartile statistical method as advocated by Trask (1932), and the method of moments advocated by Wentworth (1929) and Krumbein (1936). The last named method was the one chosen; either of the last two was given preference over the Baker method because they are common statistical methods, and the methods of moments was chosen because it takes into consideration the entire distribution of the sediment through the various grade sizes, instead of considering only the first and third quartiles. Logarithmic moments were used in which phi is the negative logarithm to the base 2 of the Wentworth grade figures. From the phi values and the percentage weight frequency, the first, second, and third moments were developed and from these the arithmetic mean, $M\phi$, the standard deviation, σ_ϕ, and the skewness, $SK\phi$, were obtained. This is a standard method which is well illustrated by Camp (1931) and adapted for use in work on sediments by Krumbein (1936).

Because phi is a logarithmic number, the measures are also logarithmic and the arithmetic mean of such phi measures are the logarithms of the geometric mean of the original measures. If the phi values then are multiplied by $-\log_2$, they are converted to the logarithms of the original measures, that is, to the sigma measures of the Wentworth scale, to the base 10. These may then be readily changed to the original ξ measures by the use of ordinary logarithm tables. In table 1, columns 2 and 3, are given the arithmetic mean of the phi deviations, $M\phi$, and its equivalent in the Wentworth scale $GM\xi$. Mills (1938) considers this a preferable measure of the central tendency where the class intervals are of equal width, and logarithmic; and this is the case when the Wentworth scale is used in histograms.

The standard deviation, σ_ϕ, of the phi measures and its ξ equivalent are given in column 4 and 5 of table 1. By the nature of the equation from which it is derived, $\sigma\phi$ is always positive. The equation is $n_2 - n_1^2 = \sigma\phi$; n_2 is always positive since it is the square of the deviations above and below the zero, and whether they are negative or positive originally, they are positive when squared. For this reason then, n_2 is always greater than n_1 since $n_1 = fd^2/N$, which is equal to, or less than, n_2, or in other words d^2. N is the sum of the frequencies and is always greater than f except when all the frequencies fall into one grade, then $N = f$ and $n_2 - n_1^2 = 0$, in which case the standard deviation, σ_ϕ, is also zero, and $\sigma\xi$ will be 1.

It should be noticed that the numbers in table 1, column 5, increase whereas those in column 4 decrease. This is because $\xi = 1/2^\phi$, and as ϕ increases ξ will decrease, and as ϕ is always greater than zero, for the Berea sandstone computations, ξ is always less than 1.

The ϕ skewness, Sk_ϕ, and the ξ skew-

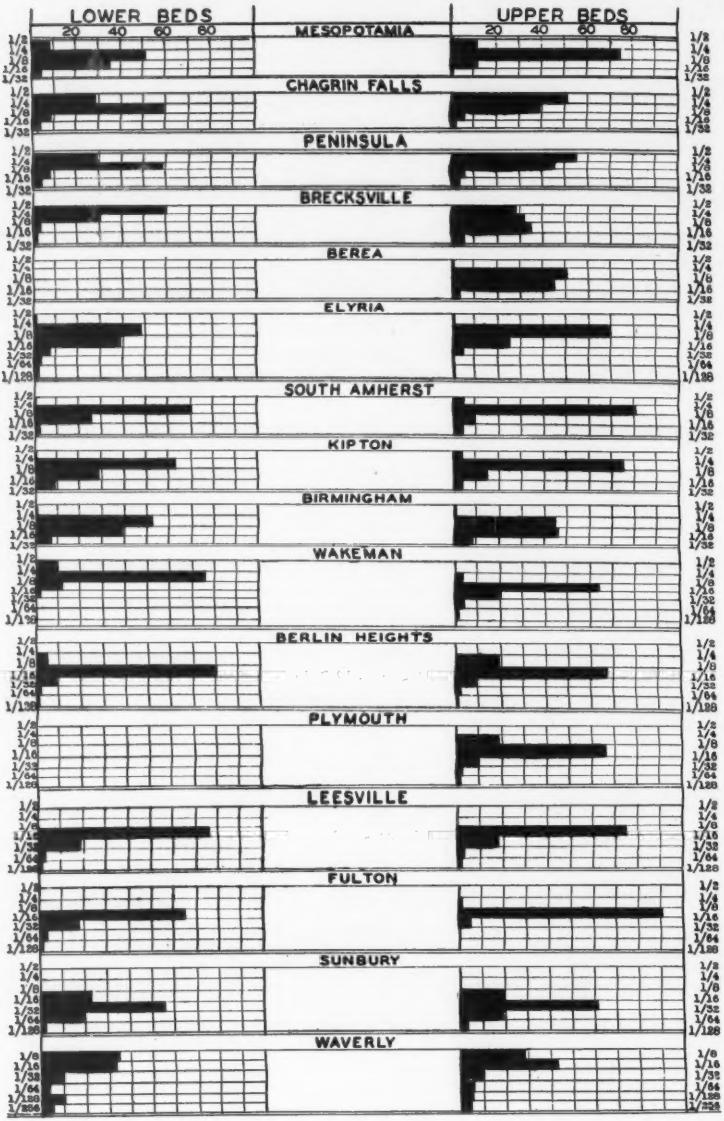

FIG. 2.—Histograms from the Berea sandstone in Ohio.

TABLE 1

	M_ϕ	GM_ξ	σ_ϕ	σ_ξ	Sk_ϕ	Sk_ξ
Mesopotamia						
38 Upper	2.525	.1737	.524	.6936	.270	.8293
39 Lower	2.838	.140	.680	.6242	.070	.9953
Chagrin Falls						
35 Upper	2.080	.2365	.713	.610	.600	.660
37 Lower	2.382	.1919	.701	.615	.402	.7474
Peninsula						
45 Upper	2.065	.2390	.746	.5963	.686	.6216
44 Lower	2.368	.1938	.710	.6113	.788	.5793
Brecksville						
43 Upper	2.681	.1560	.902	.5352	.031	.9787
42 Lower	1.971	.2554	.687	.6212	.786	.5800
Berea						
27 Upper	3.007	.1241	.545	.6854	.515	.6990
Elyria						
26 Upper	2.749	.1488	.570	.6735	.740	.5988
24 Lower	3.151	.1126	.854	.5533	1.000	.5000
South Amherst						
16 Upper	2.620	.1627	.579	.6695	.225	.8556
46 Lower	2.796	.1440	.512	.7011	.584	.6671
Kipton						
7 Upper	2.698	.1541	.572	.6727	.665	.6307
2 Lower	2.815	.1412	.592	.6634	.668	.6294
Birmingham						
13 Upper	3.123	.1148	.633	.6449	.241	.8462
8 Lower	3.002	.1248	.636	.6428	.350	.7846
Wakeman						
28 Upper	3.851	.0693	.712	.6105	.921	.5292
29 Lower	2.552	.1706	.692	.6190	.346	.7868
Berlin Heights						
34 Upper	3.485	.0894	.625	.6484	.790	.5784
31 Lower	3.613	.0779	.561	.6779	.690	.6199
Plymouth						
62 Upper	3.340	.0988	.666	.6447	.596	.6616
Leesville						
56 Upper	3.795	.07207	.581	.6685	.141	.9069
59 Lower	3.794	.07218	.606	.6566	1.470	.3610
Fulton						
54 Upper	3.542	.0859	.272	.8282	.803	.7532
55 Lower	3.900	.0763	.6338	.6448	.757	.5917
Sunbury						
50 Upper	4.471	.0451	.684	.6225	.213	.8627
52 Lower	4.455	.0456	.672	.6277	.003	.9977
Waverly						
67 Upper	4.784	.0360	1.365	.3883	.770	.5864
69 Lower	4.994	.0314	1.705	.3068	.602	.6586

ness, Skξ, are shown in table 1 in the 6th and 7th. As Sk_ϕ approaches zero from either the negative or positive side the skewness becomes zero. If the number is positive, the greatest weight of the measures is on the side of the smaller diameters from the geometric mean, and if negative, on the side of the larger diameters from the geometric mean. Column 7 shows this same dis-symmetry in a different way, the skewness is zero as the number approaches 1, and is

weighted to the side of the smaller diameters as the number becomes less than 1, and to the side of the larger diameters when greater than 1.

Along the northern outcrop of the sandstone, from Mesopotamia to Wakeman, figure 1, there is no continuous variation in the geometric mean diameter, but there is a tendency toward coarser material in the Chagrin Falls, Brecksville, and Peninsula area. Newberry (1874), when first describing the Berea, assumed that the source of the material was to the northwest because, "where the Berea sandstone is exposed, the group is thickest and coarsest where it approaches nearest to the Michigan outcrops," but as table 2 shows that at South Amherst, Birmingham, and Kipton, where the sandstone is thickest, it is decidedly finer than it is farther east. A pebbly horizon in the central part of northern area is mentioned by Orton (1888), and a few pebbles of white quartz were found by the authors but they occur infrequently. These range to half an inch in diameter and have variable roundness. They were most common near the base of the formation in the Brecksville region but were not limited to this horizon. Bownocker (1915) records the pebbles as found only in Summit county and there only occasionally. Pebbles were not found in any samples collected and, because of their infrequency, no pains were taken to make certain they were included.

There is no vertical variation in texture which may be termed significant. This is shown by table 1. This lack of vertical variation is better brought out in table 2 where data, similar to that in table 1, are given on regularly spaced samples from the thick beds of Kipton, South Amherst, and Birmingham quarries. This variation is no more than could be expected from any sandstone in which cross-bedding and ripple marks are common. Ripple marks are of oscillation and current types. These current ripple marks occasionally show current cross ripples, which suggest variable velocities in the water, horizontally and vertically. Under such conditions, a well sorted sandstone with but little fine material, and having a somewhat variable median diameter, is to be expected; that is to say, one in which the standard deviation is small and the skewness slight.

The north-south line of outcrop from Berlin Heights to Waverly does show a very definite variation in texture. The change in the geometric mean diameter from the north to the south is from about .08 mm. to about .03 mm. and is almost linear, thus showing a progressive change from a fine sandstone at Berlin Heights to very fine sandstone at Sunbury and to siltstone at Waverly. This is the same for both the upper and for the lower beds, a continuous variation in texture that is entirely lacking along the northern exposures.

The standard deviations, given in columns 4 and 5, table 1, are very similar in all the samples except at Waverly, the outcrop farthest south. All the samples are well sorted as can also be readily seen in figure 2 where the histograms have 80 per cent or over of the material in one or two grades, the only exception being in the upper beds at Brecksville where they are just below 70 per cent in two grades, and even here some 95 per cent is in three adjacent grades. The Waverly sample (lower bed), shows a great increase in the clay size particles and $\sigma\xi$ decreases to .3068. This large change in the textural deviation is accentuated in the moments method because this method emphasizes those measures farthest from the mean.

Table 2 shows that there is even less textural variation in the thick vertical sections than elsewhere. Only one, that at South Amherst shows any distinct vertical trend, the lower beds showing slightly better sorting than the upper ones; but even here, the change is slight.

Skewness, shown in columns 6 and 7 in tables 1 and 2, is for the most part slight. In every case except one, the Sk_ϕ is positive and consequently the $Sk\xi$ less than one. This exception, shown in table 2 sample 9, is in the Birmingham sample.

All of the other samples have more material on the side of the smaller diameters from the geometric mean.

There is no doubt that the changes which take place in an ancient sediment are more likely to affect the finer particles than the coarser, especially when these smaller particles are of clay material and the coarser ones are predominantly of quartz grains. The tendency is for the clay to form new minerals which are coarser than the original. Other factors, among which are infiltration, deposition and solution will also tend to change the original textural variation and this change will again be greatest in the finer grades. A petrographic study of the Berea, which is now being made and will be reported later, shows some secondary calcite and secondary amorphous silica cementing the sand grains. There is no doubt that on disaggregation the cementing calcite will be fractured and fall in the finer grades.

It is obvious that over the northern part of the state, the Berea sandstone is well sorted. This is possible in a formation which is characterized by features associated with moving water (Trask, 1932). Well sorted sands may be due to particles of about the same size coming into the basin of deposition, to moving water some distance above the floor of the basin, or to water washing the floor of the basin. Because of the north-south variation in mean grade-size, it appears unlikely that the sediment was well sorted as it came into the area, and the above mentioned cross-bedding and ripple marks are good evidence that the water immediately above the floor was not still. It seems then that the Berea

TABLE 2

From the Kipton Quarry

Numbers 2, 3, 4, 5, 6, 7 are respectively 1, 6, 12, 23, 45, and 40 feet from the top of the sandstone exposed at the quarry.

	M_ϕ	GM_ξ	σ_ϕ	σ_ξ	Sk_ϕ	Sk_ξ
No. 2	2.815	.1412	.592	.6634	.668	.6294
No. 3	2.936	.1307	.650	.6878	.540	.6878
No. 4	2.720	.1518	.652	.6320	.571	.6732
No. 5	2.944	.1300	.612	.6543	.491	.7116
No. 6	2.898	.1428	.596	.6607	.593	.6630
No. 7	2.698	.1341	.572	.6727	.665	.6307

Amherst Quarry

Numbers 16, 1, 14, and 46 are respectively 1, 40, 102, and 150 feet from the top of the sandstone exposed at the quarry.

	M_ϕ	GM_ξ	σ_ϕ	σ_ξ	Sk_ϕ	Sk_ξ
No. 16	2.620	.1627	.579	.6695	.225	.8556
No. 1	2.744	.1493	.552	.6821	.675	.6263
No. 14	2.727	.1511	.528	.6935	.905	.5340
No. 46	2.796	.1440	.512	.7011	.584	.6671

Birmingham Quarry

Numbers 13, 11, 9, and 8 are respectively 1, 21, 44, and 58 feet from the top of the sandstone exposed at the quarry.

	M_ϕ	GM_ξ	σ_ϕ	σ_ξ	Sk_ϕ	Sk_ξ
No. 13	3.123	.1148	.633	.6449	.241	.8462
No. 11	3.112	.1157	.625	.6484	.190	.8766
No. 9	3.151	.1126	.649	.6377	−.185	1.2774
No. 8	3.002	.1248	.636	.6428	.350	.7846

sandstone is a typical current-bedded deposit (Bailey, 1936) in which the main direction of flow was to the south.

SHAPE ANALYSIS

In the past few years a number of methods have been proposed to determine sphericity and shape of clastic particles. For grains less than one-half mm. in diameter, it is customary to make projection areas of a number of the grains and from these projections, the roundness or shape of the grain is computed. The method chosen in this investigation is that of Tickell (1938) in which T (roundness number) = grain area/circle area. The circle area is the area of a circle with a diameter equal to that of the longest diameter of the grain measured. Before finally selecting the above named method, one proposed by Cox (1927–28) was tried, in which K (roundness factor) = grain area $\times 4/P^2$ in which P is the perimeter of the grain. The difficulty in obtaining accurate measurements of the perimeter with a map measure decided against this method. It was found that perimeter measurements could not be duplicated without an error up to 5 per cent for the angular grains of the Berea sandstone, and when this number is squared the error is proportionately larger, while the greatest diameter could be measured rapidly and accurately. Tickell advises that the area of the grains projected should be from a random section, but in our case this could not be done because the various grade sizes had been separated. Wadell (1935) has discussed the reliability of using the area of a grain which contains the greatest and intermediate diameters and shows that this is close to the true sphericity value for quartz grains. Wadell used a method for computing the roundness which is similar to Tickell's except that the diameter of a circle, equal in area to the area of the sand grain, is divided by the diameter of the circumscribing circle according to the formula $\phi = dc/Dc$, where phi is the roundness factor, dc the diameter of the circle equal in area to the grain measured and Dc the diameter of the circumscribing circle. It will be seen that if phi is squared it will be equal to the T of Tickell's formula. The reason Wadell's method was not used in this paper is because it was felt inadvisable to use phi again when it had already been used for a different purpose and also the formula used makes a greater spread between the roundness numbers, for example, the Wadell roundness value phi for a cube is .80, the Tickell roundness factor, T, is .64, while that for the sphere is 1 for both.

SHAPE ANALYSIS AS APPLIED TO THE BEREA SANDSTONE

It was necessary to clean the grains in many samples before good projection images could be obtained. The objectionable coating on the grains was almost entirely due to ferric oxide and was removed by boiling the sample for about half an hour in .5N HCl to which stannous chloride was added, the amount of stannous chloride being varied according to the amount of iron in the sample. After the ferric iron was reduced by the stannous chloride and taken into solution by the acid, the grains were then washed, dried and quartered down to a small amount. From this some 200 to 300 grains were spread evenly on a slide and covered with a mounting resin of 1.65 index of refraction to give good relief.

The size of the projection was from 3 to 5 square inches, an area large enough to give accurate measurements with a polar planimeter. To make sure that there was no duplication, the slide was held in a mechanical stage and east-west direction was taken across the slide. The paper, onto which the grains were projected, was placed on a drawing board which was held at right angles to the optical axis of the microscope. Only when a grain was in the center of the field of of view was the outline drawn. Twenty-five grains from each slide were projected. It was found that these could all be put on one sheet of paper by moving the drawing board so that the image of

TABLE 3

Location	Grade Size	Upper Beds				Lower Beds			
		Mean	Average Deviation	Mean for Sample	Average Deviation for Sample	Mean	Average Deviation	Mean for Sample	Average Deviation for Sample
Mesopotamia	.351–.246 mm.	.69	.07	.71	.09	.74	.09	.66	.08
Nos. 38, 39	.175–.147	.72	.09			.64	.08		
	.124–.104	.69	.09			.66	.10		
Chagin Falls	.495–.246	.68	.08	.65	.09	.65	.07	.63	.06
Nos. 35, 37	.246–.175	.62	.11			.66	.07		
	.175–.124	.63	.07			.72	.08		
	.124–.104	.61	.04			.63	.04		
	.104–.061	.66	.03			.57	.05		
Peninsula	.495–.351	.72	.07	.69	.07	.72	.07	.69	.08
Nos. 44, 45	.351–.246	.71	.08			.69	.08		
	.246–.175	.64	.07			.64	.08		
	.175–.124	.67	.07			.66	.08		
	.124–.061	.62	.08			.64	.05		
Brecksville	.495–.351	.72	.07	.69	.08	.72	.07	.64	.08
Nos. 42, 43	.351–.246	.71	.08			.71	.09		
	.246–.147	.65	.07			.65	.12		
	.147–.104	.64	.11			.67	.11		
	.104–.061	.65	.10			.60	.10		
Berea	.495–.246	.70	.08	.65	.10				
No. 27	.246–.147	.65	.09						
	.147–.104	.63	.10						
	.104–.061	.64	.11						
Elyria	.351–.246	.69	.07	.65	.09	.72	.08	.64	.10
Nos. 26, 24	.246–.147	.64	.08			.65	.12		
	.147–.104	.68	.08			.64	.10		
	.104–.061	.62	.10			.65	.05		
S. Amherst	.351–.246	.69	.7	.71	.08	.68	.10	.64	.10
Nos. 16, 46	.246–.147	.71	.8			.66	.09		
	.147–.104	.67	.8			.63	.12		
	.104–.061	.61	.10			.57	.10		
Kipton	.351–.246	.69	.07	.64	.09	.70	.07	.69	.11
Nos. 7, 2	.246–.175	.64	.08			.68	.08		
	.175–.147	.65	.09			.71	.09		
	.147–.104	.64	.08			.70	.09		
	.104–.061	.61	.09			.62	.07		
Birmingham	.351–.246			.67	.08	.64	.07	.66	.08
Nos. 13, 8	.246–.175	.65	.06			.64	.08		
	.175–.147	.73	.07			.63	.09		
	.147–.104	.69	.07			.69	.09		
	.104–.061	.63	.11			.67	.08		
Wakeman	.495–.246			.65	.08	.68	.09	.66	.09
Nos. 28, 29	.246–.175	.64	.08			.64	.08		
	.175–.147	.66	.05			.68	.10		
	.147–.104	.60	.07			.66	.09		
	.104–.061	.66	.05			.68	.09		
Berlin Heights	.175–.147	.66	.11	.65	.10	.69	.09	.63	.09
Nos. 34, 31	.147–.104	.66	.09			.68	.10		
	.104–.061	.62	.11			.61	.09		
Plymouth	.246–.175	.66	.12	.67	.08				
No. 62	.175–.147	.68	.06						
	.147–.104	.67	.03						
	.104–.061	.66	.10						
Leesville	.147–.104	.68	.07	.67	.06	.69	.09	.68	.09
Nos. 56, 59	.104–.061	.66	.06			.68	.08		
Fulton	.147–.104	.66	.02	.69	.07	.65	.09	.65	.08
Nos. 54, 55	.104–.061	.70	.09			.65	.08		
Sunbury	.147–.124	.69	.08	.62	.04			.72	.08
Nos. 50, 52	.124–.104	.67	.07			.68	.08		
	.104–.061	.61	.04			.72	.08		
Waverly	.124–.104	.68	.07	.65	.06	.67	.07	.65	.08
	.104–.061	.63	.06			.64	.08		

Average Mean Upper Beds .665
Average Deviation Upper Beds .077

Average Mean Lower Beds .660
Average Deviation Lower Beds .086

the different grains would fall on different parts of the paper. There was overlapping of many of the grains, but by using colored pencils in drawing the outlines of grains they could be used in the following operations without getting them confused.

As a check against the roundness values obtained in the above method, the outlines of grains from thin sections, cut normal to the bedding planes and also parallel to the bedding plane, were projected. Their areas and greatest diameters were measured and the roundness number projected; these are given in table 4.

TABLE 4

Thin sections cut normal to the bedding	Mean	Average Deviation
No. 39 Mesopotamia	.61	.07
No. 35 Chagrin Falls	.59	.09
No. 42 Brecksville	.62	.08
No. 24 Elyria	.61	.08
No. 14 S. Amherst	.58	.07
No. 29 Wakeman	.61	.09
No. 56 Leesville	.61	.06
No. 54 Fulton	.75	.08
.62—average mean .078—average A.D.		

Thin sections cut parallel to the bedding	Mean	Average Deviation
No. 39A Mesopotamia	.63	.07
No. 24A Elyria	.65	.09
No. 16 S. Amherst	.66	.08
No. 7 Kipton	.66	.10

The arithmetic mean for the grains of a given size was computed in the usual way by adding the separate roundness numbers and dividing by the number of grains measured; these are given in columns 3 and 7 of table 3. To show the amount of variation of the grains from this mean, the average deviation also was computed. A simple formula given by Kelly (1913) in which most of the computing can be done with an adding machine, was used. The accuracy of this formula is very close to the standard deviation, and Kelly recommends it for groups which are not divided into class intervals. This formula, known as the Wald-Herring formula, is as follows, $AD = 2/N(FM - \sum^{F}_{1} X)$, where AD is the average deviation; N the total number of grains measured; F the number of grains whose roundness number lies below that of the mean; M the mean roundness; $\sum^{F}_{1} X$ is the sum of the roundness numbers of the grains whose roundness is less than the mean. The average deviation for each sand grade is given in columns 4 and 8 of table 1. In columns 5 and 9 of table 1 are given the average means and their deviations for each sand sample. These were found by weighting the mean and average deviation of each grade size with the weight percentage in each grade. No grains, which passed through the .061 mesh screen, were used in this analysis.

There is no noticeable trend either vertically or horizontally in the roundness of the grains of the Berea sandstone, either along the east-west line of outcrop or along the north-south line of outcrop. That the grains do tend to arrange themselves so that their axes of greatest and intermediate diameter are parallel to the plane of deposition is clearly shown in table 3, where the roundness factor for the grains in the 8 sections cut normal to the bedding give an average mean of .62 and an average deviation of .078. However, for the disaggregated grains there is an average mean roundness of .665 and average deviation of .077 for the upper beds, and an average mean of .660 and an average deviation of .086 for the lower beds. These last figures are very close to those obtained from thin sections cut parallel to the bedding where an average mean of .65 and an average deviation of .085 is obtained. There is no doubt that random sections would give values intermediate to those cut normal and to those cut parallel to the bedding plane.

An effort was made to determine the greatest angularity that quartz grains might be expected to show. A piece of white vein quartz was broken by tapping in an agate mortar then sieved into 6

grade sizes from .495 to .061. Fifty grains of each grade size were measured and gave an average mean roundness number of .536 and an average deviation of .107. Of course, the writer recognizes that freshly broken quartz grains under natural conditions of disintegration may give a somewhat different roundness factor to those broken mechanically, but it seems reasonable to suppose that this figure does approximate to the conditions of maximum angularity, or minimum roundness. If this is true, then the Berea sandstone has undergone a certain amount of rounding but still belongs in the angular group of sandstones.

It is interesting to compare the results of this study to those MacCarthy (1933) made on the rounding of beach sands in the Delaware-Chesapeake Bay area. MacCarthy finds that the sands become more angular in the direction of their migration, so that the finer size-fractions which have travelled some 130 miles along the coast are less round than the coarser size-fractions which have not travelled this distance. He uses the Cox roundness number and it is somewhat difficult to make a comparison with the Tickell method, but a study of some 1000 grains of the Berea, using the Cox method, shows a roundness number of .83 for the upper and .82 for the lower beds. This compares very closely to MacCarthy's .800 and .860 for the finer grades of beach sands. There is neither tendency in the Berea sandstone to show greater angularity in the finer sizes than in the courser grades, nor is the roundness factor largest in those grade-sizes, which make up the greater proportion of the sample. In fact, the most noticeable thing about the Berea is that it has about the same degree of angularity in all grade sizes, and this uniformity extends vertically and horizontally through all the sections studied.

CONCLUSIONS

1. In northern Ohio, the Berea sandstone is fine grained and shows but little variation in an east-west direction, but as the outcrop is followed southward, it becomes increasingly finer grained and grades into a siltstone in southern Ohio.

2. There is no significant vertical variation in the texture in any outcrops studied.

3. The Berea is definitely classified as a sandstone of angular grains, the angularity being about the same in all localities and in all grade sizes.

4. A possible source of the Berea sandstone in Ohio was the Laurentian Highland to the north.

REFERENCES

NEWBERRY, J. S., *1874, Ohio Geol. Survey*, vol. 2, pt. 1, p. 88.

ORTON, E., *1888, Ohio Geol. Survey*, vol. 6, p. 35.

STOUT, W., *1916*, Geology of Southern Ohio: *Ohio Geol. Survey*, 4th ser., Bull. 20, p. 667.

KRUMBEIN, W. C., *1932*, Mechanical analysis of fine grained sediments: *Jour. Sedimentary Petrology*, vol. 2, pp. 140–149.

BAKER, H. A., *1926*, Equivalent grade of a sediment: *Geol. Mag.*, vol. 37, pp. 363–370.

TRASK, P. D., *1932, Origin and Environment of Source Sediments of Petroleum*, pp. 67–76.

WENTWORTH, C. K., *1929*, Method of computing mechanical composition types in sediments: *Geol. Soc. America, Bull.*, vol. 40, pp. 771–790.

KRUMBEIN, W. C., *1936*, Application of logarithmic moments to size frequency distribution of sediments: *Jour. Sedimentary Petrology*, vol. 6, pp. 35–47.

CAMP, B. H., *1931, Mathematical Part of Elementary Statistics*, pp. 18–33.

MILLS, F. C., *1938, Statistical Methods* (Revised), 129.

BOWNOCKER, J. A., *1915*, Building Stones of Ohio: *Ohio Geol. Survey*, Bull. 18, p. 75.

BAILEY, E. B., *1936*, Sedimentation in relation to tectonics: *Geol. Soc. America, Bull.*, vol. 47, pp. 1715–1717.

TICKELL, G. F., *1938, Examination of Fragmental Rocks*, p. 6.

COX, E. P., *1927–28*, A method of assigning numerical and percentage value to the degree of roundness: *Jour. Paleontology*, vol. 1, pp. 175–183.

WADELL, H., *1935*, Volume, shape, and roundness of quartz particles: *Jour. Geology*, vol. 43, pp. 264–269.

KELLY, T. L., *1913, Statistical Methods*, pp. 71–73.

MACCARTHY, G. R., *1933*, Rounding of beach sands: *Am. Jour. Sci.*, vol. 25, pp. 205–244.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 2, PP. 58–64, FIGS, 1–3, TABLE 1, AUGUST, 1940

AREAL VARIATIONS OF CALCIUM CARBONATE AND HEAVY MINERALS IN BARATARIA BAY SEDIMENTS, LOUISIANA

L. T. CALDWELL
State Teachers College, De Kalb, Illinois

ABSTRACT

This paper is a report on a continuation study of the sediments of Barataria Bay. Former studies made of these Mississippi delta sediments included sediment size and organic carbon content. The present paper includes the calcium carbonate content and heavy mineral content. The analytical data are used to prepare maps of areal distribution of acid solubles and heavy minerals. The data are compared to show parallels existing between the areal distribution of calcium carbonate and heavy minerals. The heavy minerals, when separated from the sand fractions of the samples, show a distribution pattern in which high heavy mineral content parallels low calcium carbonate content.

A comparison with earlier published data shows that high calcium carbonate is associated with fine sediments and high organic carbon, whereas high heavy mineral values are associated with coarser sediments and low organic carbon. The outstanding feature of the study is that the environmental patterns disclosed by heavy minerals and acid solubles agree well with the pattern shown by size, sorting, and organic carbon.

INTRODUCTION

The sediments of Barataria Bay, La. have been studied for sediment size (Krumbein and Aberdeen, 1937). and organic carbon content (Krumbein and Caldwell, 1939). This paper is a report of a further study in which the calcium carbonate and heavy mineral content of the same samples are described in respect to their areal distribution in Barataria Bay. Comparisons are made with the size of the sediments and with their organic carbon content.

For a detailed description of Barataria Bay and the collecting of the samples the reader is referred to former papers reporting upon studies made of these same sediments (Krumbein and Aberdeen, 1937), (Krumbein and Caldwell, 1939), (Krumbein, 1939). Figure 1, reproduced from an earlier report, is a map of a part of the bay, showing the sample localities, each of which is identified by a sample number. This map also shows the depth of the water in feet (Roman numerals) and furnishes a general picture of the environment.

CALCIUM CARBONATE CONTENT OF SAMPLES

A N/10 solution of hydrochloric acid was used in treating the samples for acid soluble minerals. Air dried samples of approximately two grams in weight were treated with an excess of acid. The residue of minerals not dissolved by the acid was taken as the weight of the acid insolubles. The loss in weight was taken as the amount of acid soluble material. Percentages were calculated from the loss in weight. These percentages were taken by the writer to consist largely of calcium carbonate, since chemical analyses of a few representative solutions resulting from the treatment showed a high calcium content.

The percentages of calcium carbonate were plotted on a map of Barataria Bay, each value at its corresponding sampling point. The area was then divided into groups of samples having less than 5.0 per cent of calcium carbonate, from 5.1 to 10.0 per cent of calcium carbonate, and so on, the last of the five groups containing more than 20.0 per cent. The

corresponding contour lines afford a basis for dividing the bay into areas as shown on figure 2. The analytical data on the calcium carbonate content are given in table 1, which also includes the analytical data on heavy mineral content and corresponding sample numbers.

The contours of figure 2 indicate that sediments of lowest carbonate content extend as a belt along the gulf coast of the barrier beaches, and penetrate into the bay through the several passes much as did the carbon content previously studied. Most of the bay is covered with sediments ranging from 5.0 to 20.0 per cent calcium carbonate, and the areas having more than 20.0 per cent are generally confined to zones fringing the low islands which define the bay. Two exceptional occurrences of high calcium

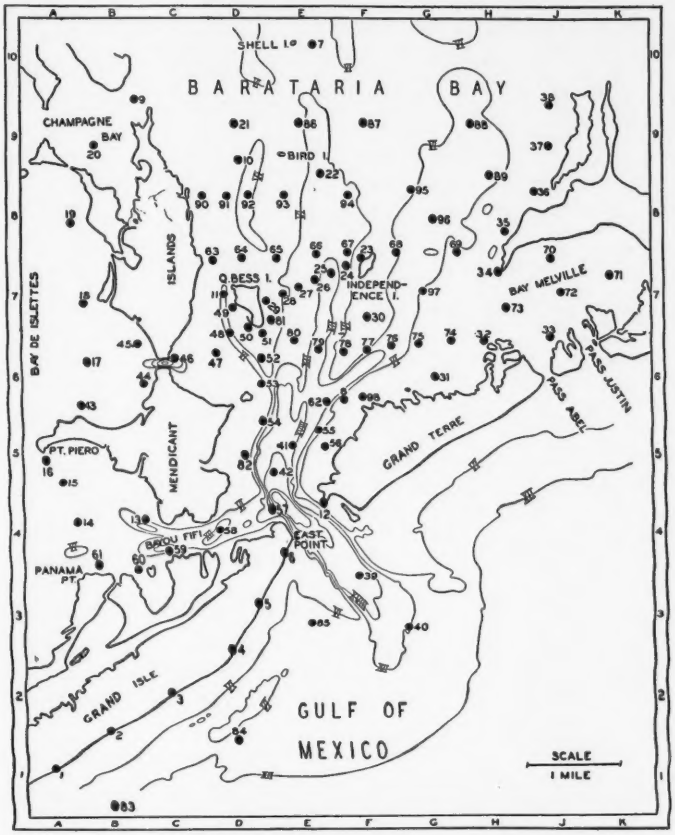

FIG. 1.—*Southern part of Barataria Bay, showing location and number of samples. Roman numerals refer to depth of water in feet.*

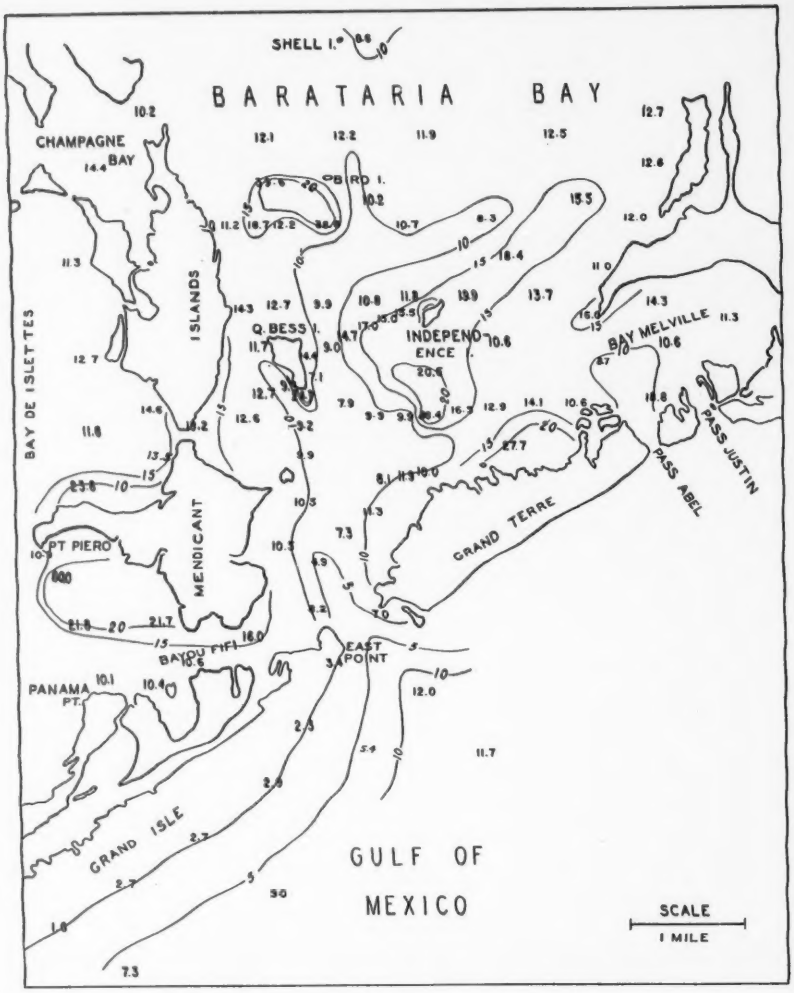

FIG. 2.—Distribution of calcium carbonate in Barataria Bay.

carbonate may be noted. One is to the southeast near Point Piero and the other lies north of Grand Terre. Both may be attributable to circulations among the several channels through the bay in terms of oyster reefs which may supply the shell material. It may also be noted that the dendritic pattern shown on this map is very similiar to the dendritic pattern of depth of water on figure 1, which is attributed to circulation of currents in such tidal lagoon environments.

DETERMINATION OF HEAVY MINERAL CONTENT

Flotation in bromoform was employed in separating the heavy minerals. Two gram samples were dispersed in N/100 sodium oxalate solution (Krumbein, 1933) to clean the sand grains of adhering clay. After dispersion, the samples were passed through a sieve with meshes of 0.061 mm. to separate the finer material from the sand. Due to the difficulty of separating the heavies from the clay fraction, combined with the clay coating on the grains, it was virtually necessary to confine the heavy mineral separation to the sand fraction. It is realized that this may yield biased data, but as a first approach it seemed desirable to see whether, under these limitations, any heavy mineral pattern would develop.

The heavy minerals of the sand fraction were separated in a small glass funnel equipped with a three-inch rubber tube and a pinch cock at the lower end. The funnel was filled with bromoform and the sand sprinkled on the liquid surface, followed by careful agitation with a small glass rod. Ten minutes were allowed for the separation to be completed. The heavy minerals were removed by opening the pinch cock and permitting about one-half of the bromoform to run into another funnel of like size. The second funnel contained a paper filter which permitted the bromoform to filter into a bottle and leave the heavy minerals on the filter. The filter and heavy minerals were dried and the weight of the heavy minerals determined on a balance. From this weight of heavy mineral residue, percentage calculations of the heavy minerals in the sand fraction were made for each of the 98 Barataria Bay samples. The results of the heavy mineral separations, expressed as percentage of sand by weight, are included in table 1.

The percentage of heavy minerals, above 2.9 specific gravity, from the sand fraction of each sample, was plotted on a map of the bay, each value at its corresponding sampling point. The area was then divided into groups of samples having less than 0.4 per cent heavy mineral from 0.41 to 0.80 per cent heavy mineral etc; The last group of samples contained more than 1.60 per cent. The corresponding contour lines afford a basis for dividing the bay into areas as shown on as shown on the map of figure 3.

The following discussion is understood to apply only to the heavy minerals of the sand fractions. The contours of figure 3 indicate that sediments of highest heavy mineral content extend into the bay through the several passes. A narrow zone extends along the center of the bay between Queen Bess and Independence Islands. Most of the bay is covered with sediments whose sand fractions contain from 0.8 to 1.6 per cent of heavy minerals; areas having less than 0.8 per cent are confined to zones fringing the islands. Three exceptional occurrences of high percentages may be noted. One is north of Pass Abel in the eastern part of the bay, which is located in a channel extending between the islands south of Bay Melville, which channel has recently been opened through the barrier at Passes Abel and Justin. Another exceptional occurrence is found in the comparatively quiet waters of Champagne Bay. These exceptional cases may be due to local concentrations of heavier sands due to circulation of waters, or they may represent sampling errors.

RELATIONS AMONG SEDIMENTARY CHARACTERISTICS

A comparison of figures 2 and 3 shows several interesting parallels. The zones of lowest calcium carbonate content include quite generally, the zones of highest heavy mineral content. Likewise, the areas of high calcium carbonate content are distributed similarly to those of low heavy mineral content. Sediments having sand fractions with heavy mineral percentages between 1.2 and 2.0 constitute very similar areas to those having calcium carbonate percentages from 0.0 to 10.0. Close to the shores of the islands which define the bay, sediments occur

TABLE 1. *Statistical characteristics of Barataria Bay samples*

Sample Number	$CaCO_3$ Percentage	Heavy Mineral Percentage	Sample Number	$CaCO_3$ Percentage	Heavy Mineral Percentage
1	1.65	1.35	51	24.70	1.13
2	2.70	1.26	52	9.25	1.20
3	2.75	1.54	53	9.95	0.91
4	2.95	1.02	54	10.55	0.91
5	2.35	0.78	55	11.30	1.10
6	3.40	0.89	56	*	*
7	8.60	1.19	57	8.25	1.40
8	7.40	1.30	58	16.00	0.58
9	10.25	1.69	59	10.60	1.20
10	39.65	0.73	60	10.45	1.81
11	11.75	0.89	61	10.15	1.17
12	7.05	0.82	62	*	*
13	21.75	0.96	63	14.35	2.02
14	21.80	0.41	64	12.75	1.02
15	80.05	0.61	65	9.95	1.39
16	10.95	0.72	66	10.80	1.13
17	11.80	0.64	67	11.85	1.03
18	12.70	0.74	68	19.10	1.25
19	11.35	0.90	69	13.70	1.67
20	14.45	2.30	70	14.35	0.91
21	12.15	0.54	71	11.35	1.62
22	10.20	1.67	72	10.65	1.33
23	60.00	3.10	73	8.70	2.41
24	15.55	1.33	74	14.15	1.45
25	15.00	1.21	75	12.95	0.86
26	17.00	1.02	76	16.50	1.15
27	14.70	1.41	77	88.40	1.20
28	9.05	1.64	78	9.95	1.43
29	14.45	1.40	79	9.90	2.59
30	20.55	1.19	8.	7.95	1.05
31	27.70	0.64	81	7.15	1.58
32	10.64	1.29	82	25.05	1.28
33	10.85	1.39	83	7.30	1.29
34	16.05	1.42	84	9.85	1.66
35	11.05	1.11	85	5.40	1.02
36	12.05	1.90	86	10.25	1.06
37	12.65	0.69	87	11.95	1.11
38	12.75	1.31	88	12.50	1.16
39	12.03	0.89	89	15.55	1.28
40	11.70	1.35	90	11.25	1.02
41	10.80	1.52	91	18.70	0.99
42	17.95	1.39	92	12.25	0.40
43	23.80	0.77	93	38.55	0.53
44	13.50	0.26	94	10.70	0.58
45	14.65	0.95	95	8.30	0.95
46	18.20	1.28	96	18.40	1.16
47	12.65	1.63	97	10.65	0.72
48	12.70	1.00	98	10.05	0.90
49	9.70	1.32			
50	9.30	1.29			

* No analyses: entire sample used in earlier studies.

with percentages of heavy minerals below 0.8 per cent and calcium carbonate content of above 15.0 per cent.

When the areal distribution of the heavy mineral values are compared with the size distribution of the sediments reported on in an earlier paper (Krumbein and Aberdeen, 1937), it is to be

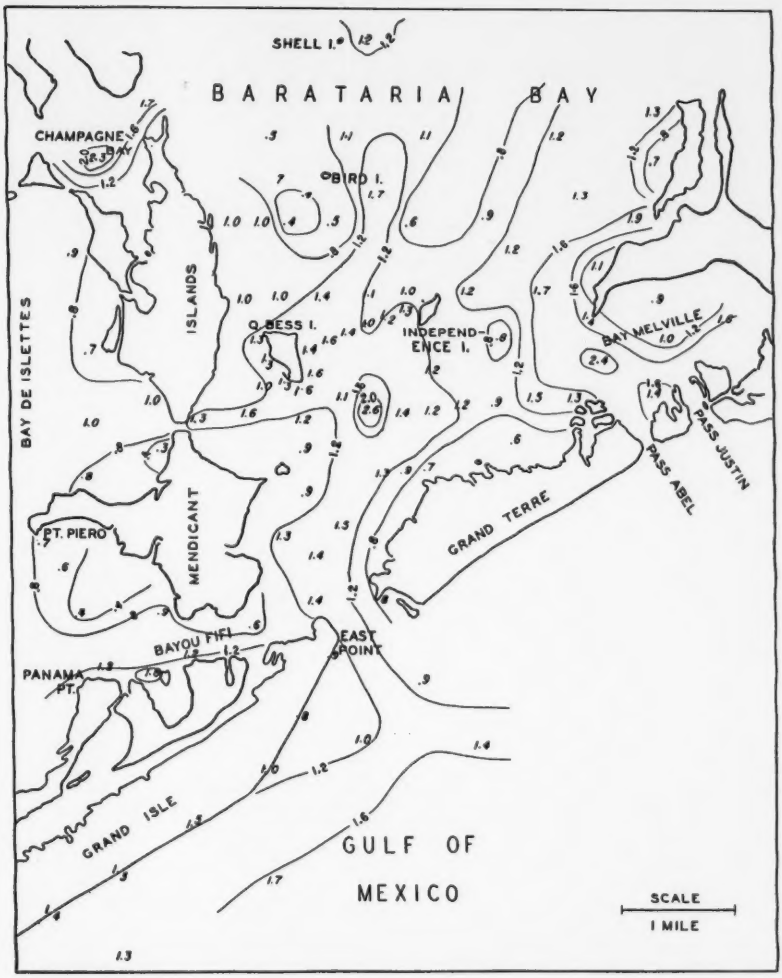

FIG. 3.—Distribution of calcium carbonate in Barataria Bay.

noted that contrary to what might be expected, the high heavy mineral values are found in the coarser sediments and the low heavy mineral values in the fine sediments. This may be understood when it is recalled that the heavy mineral distributions given by this study represent only the sand fractions of the sediments and not the entire samples. The writer realizes as a consequence that the

heavy mineral data of this study are significant largely for their general distribution pattern. It is, nevertheless, interesting that with the limitations mentioned, the heavy mineral pattern does conform to the general environmental picture derived from other sedimentary characteristics.

Inasmuch as the high heavy mineral values are associated with coarser sediments, it follows that low heavy mineral values are associated with high organic carbon content, which was shown in an earlier report (Krumbein and Caldwell, 1939), to be associated in general with fine sediments. Low organic carbon values with high heavy mineral content are found in the circulatory channels of the bay. There is also a similarity between the pattern of the areal distribution of heavy mineral values and organic carbon content. A high organic carbon value, located north of the southernmost Mendicant Island, is associated with a low heavy mineral content. The main linear zones of low organic carbon, and of high heavy mineral content, located in the central portion of the bay, have roughly the same trends.

The environmental pattern of acid solubles is very similar to that of size of sediments. The fine sediments contain the high acid soluble values, and the coarser sediments contain progressively smaller amounts. It is to be expected that recent sediments may yield better patterns of acid solubles than ancient sediments, due to variations in carbonate content occasioned by post-depositional factors of cementation or selective leaching. Whether carbonate content remains constant through geological time depends upon numerous factors. In general, it is doubtful whether carbonate content of ancient sediments reflects adequate details of the original environmental pattern.

As high carbonate and fine sediments are associated in the environment, so are high values of carbonate and high organic carbon associated. In fact, it is noteworthy that all four sediment characteristics (size, heavy minerals, organic carbon content, and acid solubles), have many features in common, although in detail there are variations to different responses of the variables to the general environmental factors.

Perhaps the most significant contribution of the study is the demonstration that a number of sedimentary characteristics yield essentially the same broad environmental pattern. This point is important in the reconstruction of ancient environments, where some of the original sediment characteristics may be modified by authigenesis and lithification.

REFERENCES

KRUMBEIN, W. C., *1933*, The dispersion of fine-grained sediments for mechanical analysis. *Jour. Sedimentary Petrology*, vol. 3, pp. 121–135.

KRUMBEIN, W. C., and ABERDEEN, ESTHER, *1937*, The sediments of Barataria Bay. *Jour. Sedimentary Petrology*, vol. 7, pp. 3–17.

KRUMBEIN, W. C., and CALDWELL, L. T., *1939*, Areal variation of organic carbon content of Barataria Bay sediments, Louisiana. *Am. Assoc. Petroleum Geologists, Bull.*, vol. 23, no. 4, pp. 582–594.

KRUMBEIN, W. C., *1939*, *Recent Marine sediments* (A symposium). Tidal lagoon sediments of the Mississippi delta.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 2, PP. 65–77, FIGS. 1–3, TABLE 1, AUGUST, 1940

BEACH SEDIMENTS OF TROUT LAKE, WISCONSIN

V. E. McKELVEY
University of Wisconsin, Madison, Wisconsin

ABSTRACT

The beach deposits in a bay of Trout Lake in northern Wisconsin, are divided into eight textural zones which parallel the shore. The sediments of these zones are described and compared with each other, using data derived from 103 mechanical analyses. Samples collected at the same points on the beach, and others collected at points of equal distance from the water's edge, are compared to show textural changes taking place on the beach. The accuracy of sampling is tested by eight sets, of four samples each, taken at the same time and place.

INTRODUCTION

Trout Lake is located in Vilas County in the northern upland of Wisconsin, about 95 miles north of Wausau. The terrane in the immediate vicinity of the lake consists of outwash (Thwaites, 1929, pp. 109–125) and thin till (Fries, 1938, pp. 305–322), the latter present on the southeast side of the lake. Trout Lake consists of a northern and a southern basin, connected by a narrow strait. The area of the north basin is 1,318 acres, and the area of the south basin is 2,529 acres. The present discussion is limited to the beach deposits of the bay on the northeast end of the south basin.

The field work at the Trout Lake limnological station was financed by the Wisconsin Alumni Research Foundation and grateful acknowledgment is made for this support. The laboratory work was done in the University of Wisconsin sedimentation laboratory. The writer is indebted to Mr. Nelson Rodgers of the bacteriology department of the University of Wisconsin for collecting some of the samples, and to Dr. W. H. Twenhofel of the Wisconsin University department of geology for helpful criticisms and suggestions.

PURPOSE OF STUDY

In connection with lake studies carried out during the summer of 1939 at the Trout Lake limnological station, it was found that the beach deposits of the northeast bay of the south basin of Trout Lake were made up of textural zones, or bands, paralleling the shore line. The existence of environmental zones, originating through variations in degree and kind of wave action in operation on the beach, has long been known. However, very little detailed work has been done on the relation of texture to these zones. Composite samples of beach sands have been studied by Krumbein (1938, pp. 653–658) and by Evans (1939, pp. 28–31), both of whom found linear textural variations, even though the samples studied were not collected from individual sedimentation units. Consequently, it is hoped that the description of the textural zones found at Trout Lake will supplement the information already available, and perhaps, provide additional criteria for distinguishing beach deposits from other sediments.

FIELD AND LABORATORY PROCEDURE

Samples for textural comparison should be collected from units which have the same environmental origin and must not be mixed. Unless samples from similar units are analyzed, grain distribution, sorting, and other statistical measures lose much of their sedimentational significance. Competency differs from time to time and from place to

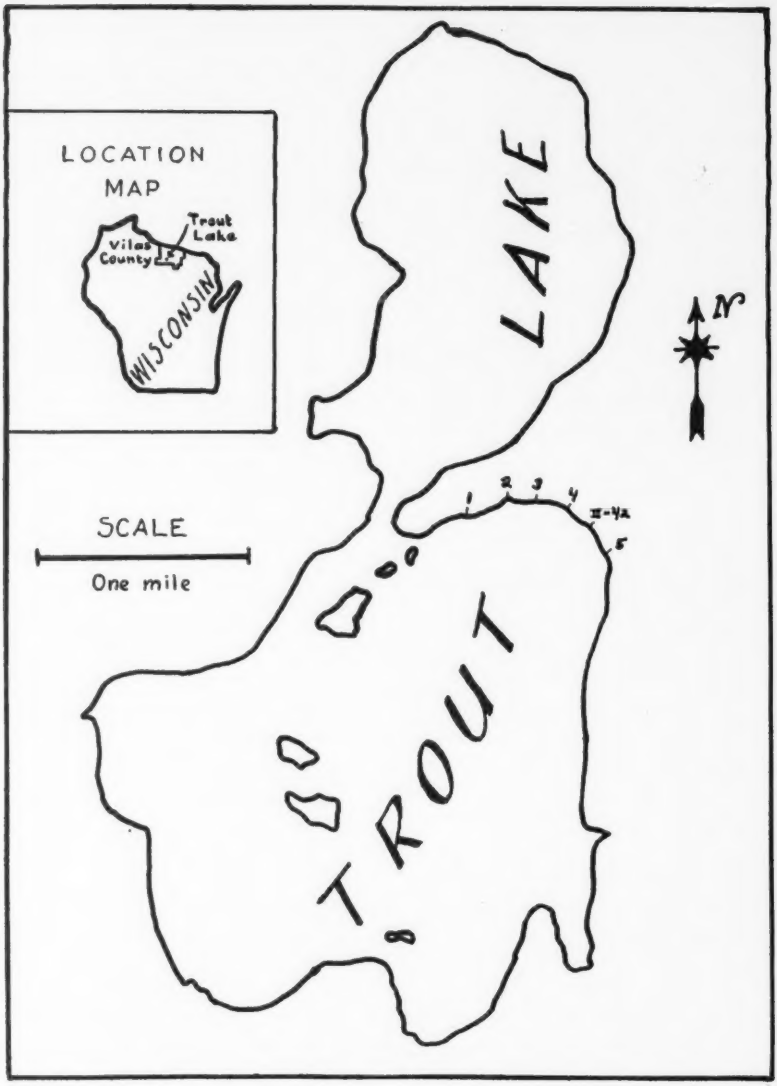

FIG. 1.—Outline map of Trout Lake, showing location of lines, or ranges, along which samples were taken. The inset shows the location of Trout Lake with respect to Wisconsin.

place in the same environment. These differences in competency are reflected in the texture of the resulting sediments. If samples are collected with no regard to the phase or sedimentation unit to which they belong, this reflection of competency in sorting and grain distribution is lost. This concept of sampling has been discussed recently by Apfel (1938, pp. 67–69) and by Otto (1938, pp. 569–582), and its significance and importance deserve considerable emphasis. The idea may not be new, but it has been neglected in many textural studies.

With this concept of sampling technique in mind, samples were collected along six lines or ranges perpendicular to the shore (see fig. 1). Samples were taken at the surface from each textural zone crossed along the range. These samples were collected on the same day, and an attempt was made to take only the sediments of the surface lamina (this may not have been achieved in those samples collected under water).

In addition to the above samples, other samples were collected by Mr. Nelson Rodgers of the bacteriology department of the University of Wisconsin in connection with bacteriological studies. These samples were collected on a range in front of the Trout Lake limnological laboratory. Collections were made several times throughout the season. The samples were taken the same distance from a constant point on the beach. Eight sets of four samples each were also collected to test the accuracy of sampling.

The samples collected consisted mainly of sand and fine gravel and contained almost no silt or clay. The sands were placed in a nest of U. S. Standard Sieves, shaken for 10 minutes in a Ro-Tap shaker, and the separates weighed. The water of Trout Lake is soft, and it was not deemed necessary to wash the samples to remove salts which might be present.

The results of the mechanical analyses are expressed in phi units, devised by Krumbein, in which negative logarithms of the diameters are used, so that an arithmetic grade scale results. One mm., on the Wentworth scale is equal to 0 on the phi scale, 2mm. = −1, ½mm. = 1, ¼mm. = 2, and so on along the usual Wentworth grade scale. The quartile measures are also expressed in phi terms, and being arithmetic, are readily comparable one to another. The quartile deviation, QDϕ, is computed according to the following equation:

$$QD\phi = \frac{(Q_3\phi - Q_1\phi)}{2}.$$

Phi skewness, *Skq*ϕ is computed:

$$Skq\phi = \frac{(Q_3\phi + Q_1\phi) - 2(Md\phi)}{2}.$$

Quoting from Krumbein (1939, p. 569):

> For descriptive and comparative purposes, *Md*ϕ (or its equivalent, the median diameter), *QD*ϕ and *Skq*ϕ afford three values which enable one mentally to visualize the cumulative curve in terms of its spread and degree of asymmetry. For example, one may compare two sediments of values *QD*ϕ equal to 0.50 and 2.50 by noting that the first has one Wentworth grade between the quartiles, whereas the second has five. Likewise, if *Skq*ϕ equals 0.0 and −0.5 respectively, it is clear that the first curve is symmetrical, whereas in the second curve, the arithmetic mean of the quartiles is half a Wentworth grade to the left of the median, and, hence, the curve is definitely skewed.

The phi scale and quartile measures were chosen because of the ease with which comparison is made, and because considerable time may be saved in making the calculations.

TEXTURAL ZONES

The prevailing wind direction is from the southwest during the summer months. The waves have a fetch of about three miles and, consequently, the bay at the northeast end of South Trout Lake is subject to considerable wave activity, particularly at the north end of the bay.

A wave-cut cliff (zone A*) is present

* The various zones are lettered for convenience in table 1 and figures 2 and 3.

almost everywhere along the margin of the northeast bay. The face of the cliff ranges in height from 1 to 5 feet. At the north end of the bay, the cliff exposes old ice ramparts composed of heterogeneous material which has been shoved up from the beach. The cliff here is fronted by a shore (defined as that portion extending from low-water mark to the base of the cliff) which is wide enough to prevent active wash at the base of the cliff. Consequently, there is no washed zone in the lower part of the cliff. On the eastern and western margins of the bay the banks rise rather abruptly, and there are no ice ramparts and no shore. Wave-cut cliffs are present, usually exposing sandy outwash. The base of the cliff is washed well here and consists of cobbles (2 to 6 inches in diameter) faced in many places by roots. This facing of roots and stones doubtless prevents rapid erosion; erosion does take place, however, as is indicated by trees which are leaning over the water, or by those which have fallen into the water as they have been completely undermined.

At the north end of the bay, a well defined shore is present. The backshore (defined as that portion of the shore that is covered by water only during exceptional storms, zone B) is predominantly composed of medium to fine sand with occasional pebbles and cobbles derived from the ice ramparts. Although the sediments of this zone are well sorted, they have a characteristic size distribution from pebbles to fine sand. The backshore varies around 3 feet in width.

The backshore is separated from the foreshore (defined as the zone between ordinary high and low water marks) by the swash-line (zone C) which, in places, consists of a pebble concentrate as well as debris in the form of sticks, twigs, and shells. The pebbles on the swash-line zone result from the washing away of

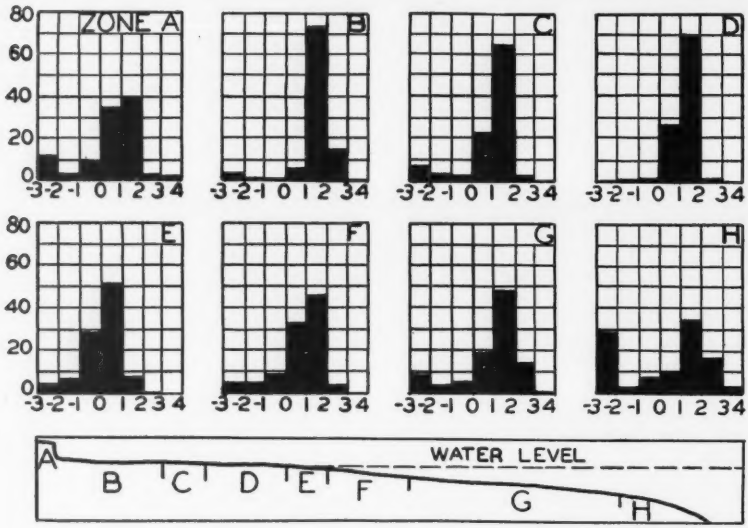

FIG. 2.—Histograms of mechanical analyses of samples representative of the textural zones. The analyses are plotted in phi units. The location of the zones is shown on a diagramatic profile of the beach.

finer material, and from pebbles which are rolled up the beach by heavy waves, the backwash of which is not able to carry them back to the plunge-line (defined as the zone where the waves break upon the shore). The swash-line zone at the north end of the bay usually averages 6 inches to 2 feet in width. Its position on the beach varies with the height of the waves.

The limits of the foreshore (zone D) are defined by the swash-line and the plunge-line. It is composed of well sorted, coarse to medium sand. The foreshore is subject to constant wash, in contrast to the backshore, and contains less fine and very fine sand. The foreshore ranges from 2 to 5 feet in width.

The sediments at the plunge-line (zone E) at the north end of the bay consist of coarse and very coarse sand. The sorting in this zone is similar to that of the foreshore sediments. The plunge-line zone ranges from 1 to 2 feet in width. Along the east and west margins of the bay there is no shore, and the waves break against the base of the cliffs; consequently, the features of the plunge-line zone, foreshore, and backshore are missing.

Immediately lakeward from the plunge line zone is a zone made up of well-washed cobbles, covered occasionally by patches of medium sized sand (zone F). The sand is not well sorted and is usually rippled. This zone is from 4 to 12 feet wide and probably represents that area over which the waves first begin to break. It is present in all parts of the bay and is widest at the north end of the bay.

The sand-gravel zone grades rather abruptly into well-rippled, medium to fine sand (zone G). The sorting is similar to that of the sand in the preceding sand-gravel zone. At the north end of the bay, this zone extends out into the lake beyond the depth of visibility. Along the east and west margins of the bay the rippled zone is rather narrow, being 4 to 8 feet wide, and is only a thin veneer of sand over cobbles.

Along the east and west margins of the bay, the rippled zone is followed by a zone made up of dirty sand and plant-covered cobbles which show no effects of wave action (zone H). This zone extends lakeward as far as observation is permitted by the visibility of the water.

RESULTS OF TEXTURAL ANALYSES

Wave-cut Cliff (*zone A*)—Five samples of the materials composing the wave-cut cliff were analyzed. Samples 1–1 and 2–1 were collected from the outwash on the west margin of the bay and show considerable heterogeneity in size distribution. Samples 3–1, 4–1, and 5–1 were collected in old ice ramparts exposed by the cliff at the north end of the bay. These samples show more uniformity, the median on the phi scale (Mdϕ) ranging from 0.6 to 1.28 and the quartile deviation (QDϕ) from 0.69 to 1.53.

Backshore (*zone B*)—Thirty-three samples were collected from the backshore. The analyses show a rather wide variation in size distribution but illustrate some consistent features. Mdϕ ranges from 0.75 to 1.94 but in 27 of these samples, it is confined to the range of 1.50 to 1.94, the dimensions of medium to fine sand. QDϕ ranges from 0.10 to 1.50 but in 31 of the samples ranges from 0.19 to 0.45. All but five of these samples are skewed to the left of the median. Skqϕ has a total range of 0.14 to -0.75. Skqϕ in 27 of the samples ranges from 0.03 to -0.20. Four sets of samples (II–6–8, III–6–8, 7–6–8, and 9–6–7) show uniform decrease in coarseness and quartile deviation in the backshore going toward the cliff. This indicates the direct effect of decreasing competency of the waves, with distance traveled up the beach, on the size of particles transported and deposited in the backshore.

Some of the characteristics of the backshore sediments are not obvious from the summary of the quartile measures, and an interpretation of the data may be in order. The position of the median indicates that the particles are mostly medium to fine sands. A study of table 1 shows that all of the backshore

TABLE 1. *Size frequency distributions of samples**

Sample	Date	Zone	Dist.†	4–8 mm −3–−2	2–4 mm −2–−1	1–2 mm −1–0	1–½ mm 0–1	½–¼ mm 1–2	¼–⅛ mm 2–3	⅛ mm 3	Mdφ	QDφ	Skqφ
1-1	7/ 1	A	0	22.07	6.87	4.66	16.52	45.70	3.69	.67	.95	1.61	−.94
1-2	7/ 1	F	−1.0 m	6.76	8.21	4.70	14.61	57.10	8.50	.29	1.42	.69	−.22
1-3	7/ 1	F	−2.5 m			6.18	17.40	60.80	13.40	3.08	1.80	.40	−.30
1-4	7/ 1	G	−3.5 m	2.37	2.65	6.41	28.61	50.00	9.00	1.24	1.29	.62	−.16
1-5	7/ 1	H	−4.5 m	28.71	2.27	7.83	9.06	34.30	16.20	1.85	1.12	2.02	−1.32
2-1	7/ 1	A	0	46.62	3.50	3.35	13.80	31.20	1.43	1.17	−1.32	2.05	.47
2-2	7/ 1	H	−4.0 m	43.10	4.27	2.30	10.10	33.40	5.30	.39	−.91	1.57	−.38
3-1	7/ 1	A	0	4.39	3.70	7.00	25.70	51.00	7.50	.41	1.28	.68	−.18
3-2	7/ 1	D	1.0 m			.39	24.70	71.00	3.60	.01	1.50	.39	−.21
3-3	7/ 1	E	0	2.76	3.00	11.01	49.00	33.20	1.82	.01	.75	.74	.23
3-4	7/ 1	F	−2.0 m	4.54	4.55	8.30	32.50	46.00	2.76	.13	1.06	.53	−.13
3-5	7/ 1	G	−4.5 m	2.41	2.64	5.12	21.99	59.20	7.40	.24	1.45	.53	−.12
3-6	7/ 1	G	−9.0 m	4.45	4.21	6.31	30.90	47.00	6.10	.70	1.10	.62	−.02
4-1	7/ 1	A	2.2 m	12.10	2.96	8.40	35.70	39.60	.20	.16	.74	.69	.02
4-2	7/ 1	B	1.5 m	11.00	3.25	8.20	25.20	52.00	.88	.01	1.07	.70	−.19
4-3	7/ 1	D	.8 m			.91	38.60	53.80	3.95	.02	1.28	.48	.06
4-4	7/ 1	E	0	.43	1.52	11.00	79.00	7.60	.60		.70	.23	−.07
4-5	7/ 1	F	−2.0 m			25.70	31.00	32.70	10.10	.65	.80	.80	−.05
4-6	7/ 1	G	−4.6 m	.65	1.82	6.70	28.60	56.00	6.15	.12	1.28	.55	.05
4-7	7/ 1	G	−7.0 m		3.37	7.56	18.50	67.50	3.70	.05	1.45	.47	−.17
5-1	7/ 1	A	2.0 m	18.85	12.20	8.80	17.40	37.20	4.20	.62	.60	1.53	−.61
5-2	7/ 1	B	1.5 m	19.40	11.42	5.25	20.60	42.61	.21		.75	1.50	−.75
5-3	7/ 1	C	1.1 m	18.90	40.60	18.10	14.30	8.31	.04		−1.22	.82	.22
5-4	7/ 1	D	.6 m		1.81	2.85	19.90	73.50	1.75	.01	1.70	.40	−.25
5-5	7/ 1	E	0	4.42	15.20	46.30	24.50	9.75	.38		−.10	.48	−.21
5-7	7/ 1	G	−5.8 m	11.80	7.10	3.70	13.50	57.00	6.70	.26	1.40	.77	−.37
II-1	7/ 6	E	.1 m		1.50	8.50	57.00	32.00	.49		.70	.44	.01
II-2	7/ 6	E	.35 m	1.51	1.98	12.20	62.00	21.15	.15		.57	.40	−.07
II-3	7/ 6	D	.6 m		.83	7.70	41.50	48.50	1.10		1.00	.48	.00
II-4	7/ 6	D	.85 m		.70	.99	28.00	69.00	1.40		1.35	.38	−.02
II-5	7/ 6	C	1.1 m	2.38	1.21	1.02	17.50	76.10	1.13	.03	1.50	.33	−.07
II-6	7/ 6	B	1.35 m	3.02	.19	.46	16.90	63.50	15.20	.21	1.65	.38	−.11
II-7	7/ 6	B	1.6 m			.22	3.72	75.80	20.00	.40	1.88	.21	−.10
II-8	7/ 6	B	1.85 m	1.85	.20	.45	4.43	74.10	18.80	.25	1.91	.25	−.16
III-1	7/ 7	E	.05 m	1.93	2.93	23.00	59.00	13.52	.12		.50	.92	−.12
III-2	7/ 7	E	.3 m	5.10	5.30	12.40	51.50	25.52	.28	.01	.81	.45	−.21
III-3	7/ 7	D	.55 m	.22	1.00	1.80	37.80	59.00	.56		1.20	.47	.02
III-4	7/ 7	D	.8 m	.16	1.00	1.24	25.49	70.00	.94		1.45	.46	−.06
III-5	7/ 7	C	1.05 m	5.40	.55	.61	15.70	76.40	1.52		1.50	.34	−.10
III-6	7/ 7	B	1.3 m	2.04	.62	.20	16.42	71.80	8.95	.10	1.57	.35	−.03
III-7	7/ 7	B	1.55 m	2.10	.37	.22	5.82	71.00	19.50	.33	1.76	.37	−.13
III-8	7/ 7	B	1.8 m			.10	2.73	76.00	19.95	.35	1.83	.10	.07
7-1	7/12	E	.05 m	1.46	7.35	18.40	65.00	7.90	.12		.56	.44	−.24
7-2	7/12	D	.35 m	1.40	.14	.50	21.00	74.90	2.39	.01	1.50	.35	−.09
7-3	7/12	D	.55 m	2.85	2.23	6.78	21.80	62.70	3.33	.01	1.40	.46	−.17
7-4	7/12	C	1.1 m	4.10	1.95	2.94	23.40	66.00	2.29		1.25	.36	−.02
7-5	7/12	C	1.35 m	7.30	2.33	2.09	22.25	65.00	1.06	.01	1.20	.37	−.03
7-6	7/12	B	1.6 m	3.62	.53	.20	13.65	71.50	10.10	.03	1.60	.33	−.06
7-7	7/12	B	1.85 m	3.63	.16	.09	6.02	73.60	15.80	.23	1.82	.24	−.15
7-8	7/12	B	2.1 m	.90	.16	.37	3.31	71.00	23.50	.26	1.90	.19	−.09
9-1	7/15	E	.05 m	1.40	2.26	18.30	59.80	17.60	.20		.45	.40	.00

9-2	7/15	E	.7 m	3.18	3.20	12.50	67.50	13.41	.15		.50	.27	-.02
9-3	7/15	D	1.25 m		.22	2.20	65.20	31.90	.11		.90	.23	-.06
9-4	7/15	C	1.45 m	4.30	1.12	1.80	44.10	45.10	3.22	.06	.96	.47	.07
9-5	7/15	C	1.7 m	4.52	1.17	.84	10.30	74.00	9.54	.05	1.60	.35	-.05
9-6	7/15	B	1.95 m	1.96	.43	.72	14.90	67.50	14.60	.18	1.58	.35	-.08
9-7	7/15	B	2.2 m	.89	.09	.15	5.20	74.00	19.50	.21	1.80	.23	-.08
11-1	7/19	B	2.1 m	2.95	.72	.31	11.50	76.80	7.92	.20	1.72	.31	-.14
14-1	7/26	E	0	5.20	6.27	28.50	51.73	7.42	.42	.06	.48	.42	-.08
14-2	7/26	F	-1.0 m			38.00	37.00	20.90	4.90	.10	.50	.85	.02
14-3	7/26	F	-2.0 m			16.20	24.80	45.80	11.40	.48	1.24	.65	-.18
14-4	7/26	G	-3.0 m	8.75	3.37	5.79	19.69	49.50	12.20	.69	1.25	.60	-.10
17-1	7/27	C	.5 m	14.21	6.79	13.90	45.60	18.90	.79	.14	.30	.77	-.18
23-1	8/ 3	E	0		1.30	6.77	55.02	35.70	1.52	.08	.80	.44	.05
23-2	8/ 3	E	.5 m	.84	.23	.46	63.70	34.10	.16		.81	.36	.10
23-3	8/ 3	D	1.0 m	1.17	1.02	2.18	9.20	73.33	8.68	.20	1.85	.15	-.30
23-4	8/ 3	C	1.25 m	9.35	1.29	.82	5.09	70.50	13.30	.15	1.70	.30	-.15
23-5	8/ 3	C	1.5 m	6.50	.48	.38	14.12	71.50	6.50	.15	1.57	.35	-.12
23-6	8/ 3	B	1.75 m	1.06	.07	.12	7.15	76.60	15.20	.12	1.94	.19	-.13
23-7	8/ 3	B	2.0 m			.06	7.77	81.70	9.54	.07	1.80	.19	-.38
23-8	8/ 3	B	2.4 m	1.79	.96	.68	14.50	78.50	3.56	.10	1.45	.28	-.03
29-1	8/10	C	.8 m	5.70	12.50	15.80	38.50	26.50	.34		.45	.60	-.15
29-2	8/10	C	.8 m	5.60	9.50	15.00	39.00	30.50	.23		.67	.68	-.30
29-3	8/10	C	.8 m	6.10	9.40	14.50	41.00	27.50	.23		.60	.62	-.26
29-4	8/10	C	.8 m	5.90	6.41	14.90	42.00	31.00	.27	.01	.70	.55	-.25
29-5	8/10	B	2.05 m		.04	.56	34.60	57.00	7.10	.08	1.25	.39	.08
29-6	8/10	B	2.05 m		.40	.46	35.70	55.00	8.61	.03	1.20	.39	.10
29-7	8/10	B	2.05 m			.32	36.50	55.00	8.00	.22	1.17	.40	.10
29-8	8/10	B	2.05 m			.29	34.00	57.50	7.40	.06	1.18	.37	.14
30-1	8/11	D	.8 m			.15	27.60	71.20	1.66	.02	1.40	.35	-.08
30-2	8/11	D	.8 m			.26	24.00	74.80	1.40	.01	1.45	.27	-.12
30-3	8/11	D	.8 m			.16	24.50	73.00	1.66	.03	1.39	.36	-.03
30-4	8/11	D	.8 m			.27	27.30	72.00	1.68	.02	1.35	.28	-.07
30-5	8/11	B	2.05 m	11.50	.01	.09	8.50	62.10	17.60	.13	1.66	.38	-.16
30-6	8/11	B	2.05 m	4.45	.46	.09	12.30	66.90	16.10	.10	1.65	.32	-.09
30-7	8/11	B	2.05 m	4.80	.03	.05	14.50	62.40	15.00	.14	1.75	.40	-.20
30-8	8/11	B	2.05 m		.20	.24	21.50	62.00	16.50	.09	1.55	.35	-.10
34-1	8/15	D	1.05 m		.10	1.09	63.60	35.10	.24	.01	.80	.33	.07
34-2	8/15	D	1.05 m		.01	.79	61.50	38.00	.37	.01	.85	.27	.03
34-3	8/15	D	1.05 m		.09	1.30	58.50	39.90	.45	.01	.89	.35	.01
34-4	8/15	D	1.05 m		.25	1.24	54.10	43.50	.45	.03	.95	.31	-.01
34-5	8/15	B	2.3 m	2.50	.05	.26	20.70	61.00	14.80	.08	1.50	.37	-.07
34-6	8/15	B	2.3 m	1.38	.10	.16	22.60	61.00	14.60	.13	1.48	.36	-.09
34-7	8/15	B	2.3 m		.09	.17	22.70	60.50	15.40	.27	1.57	.37	-.10
34-8	8/15	B	2.3 m	3.40	.27	.08	20.50	57.90	17.80	.11	1.60	.45	-.15
42-1	8/18	D	1.1 m	.10	3.32	3.14	26.40	65.80	.58	.05	1.35	.42	-.11
42-2	8/18	D	1.1 m		3.72	3.04	29.00	64.00	.43	.01	1.30	.44	-.10
42-3	8/18	D	1.1 m		2.78	2.71	27.40	65.50	.46	.05	1.38	.42	-.11
42-4	8/18	D	1.1 m		5.00	3.73	28.30	61.20	.29	.04	1.25	.43	-.08
42-5	8/18	B	2.35 m		.03	.18	19.40	64.10	15.90	.19	1.70	.35	-.14
42-6	8/18	B	2.35 m		.10	.63	21.02	63.10	14.60	.27	1.62	.37	-.14
42-7	8/18	B	2.35 m		.09	.78	22.10	64.00	12.58	.13	1.60	.36	-.13
42-8	8/18	B	2.35 m		.06	.16	23.80	65.00	10.70	.08	1.55	.37	-.13

* Percentages given in Wentworth and Phi Units.
† Distances measured from water's edge. Distances lakeward indicated by a minus sign.

samples contain an appreciable amount of fine sand, which is missing from most of the other zones. This is due to the fact that only occasional waves reach the backshore; these waves carry only a fine load into this zone and the backwash is not able to carry all of it back, or to remove much of the fine sand already there. The average value of QDϕ shows that most of the samples consist of medium and fine sand, but it does not indicate the range in size of the particles present. Nearly all of the samples show a size distribution from pebbles to very fine sand, and the extreme sizes are characteristic of the zone. The pebbles and granules are present in quantities of 2 to 20 per cent and are lag features, or are introduced by occasional heavy waves. The negative skewness reflects the second peak in size frequency formed by these coarse particles.

Swash-line Zone (*zone C*)—The sediments of the swash-line show an even greater variation in size distribution than those of the backshore. MDϕ in the 14 samples collected from the swash-line ranges from -1.22 to 1.70; Mdϕ in six of these samples varies from 0.30 to 0.96, and seven of the samples from 1.20 to 1.70. QDϕ varies from 0.30 to 0.37 in these last seven samples, and from 0.47 to 0.82 in the rest of the samples. All of the samples except two are skewed to the left of the median. Skqϕ in the medium sands ranges from -0.03 to -0.15; in the coarse sands, Skqϕ ranges from -0.30 to 0.07.

The swash-line samples are characterized by the presence of pebbles and granules. That these coarser particles are not always present in great abundance is illustrated by seven of the samples in which the phi median ranges from 1.20 to 1.70. This variation in the amount of coarse material present should be expected in view of the changeable position of the swash-line; a concentration of pebbles and granules is not likely to occur in the swash-line unless wave action has been rather severe and the swash-line has remained at a relatively constant position over two or three days. The medium sands described above represent the swash-line under conditions of little wave action. The sands are, on the average, coarser than those of the backshore, and finer than those of the foreshore and plunge-line zones.

The main difference between the swash-line sediments and the sediments of the backshore is the absence of fine sand in the swash-line sediments and its presence in the backshore. Then, too, coarse sand is often present in the swash-line, whereas, it is usually absent in the backshore zone, causing a secondary peak on the frequency curve of the backshore sediments.

Foreshore (*zone D*)—In the 23 samples collected from the foreshore, Mdϕ ranges from 0.80 to 1.85; in 15 of these samples Mdϕ ranges from 1.20 to 1.50. QDϕ in all of the samples ranges from 0.15 to 0.48; in 18 of the samples QDϕ varies from 0.31 to 0.48. Skqϕ is negative or zero in 18 of the samples and has a total range of -0.30 to 0.07.

From a preliminary study of these quartile measures, the foreshore sediments do not appear to have particularly distinctive characters. However, an examination of table 1 shows that the pebbles, granules, very coarse sand, and fine sand are usually missing from this zone, or, if present, occur only in very small quantities. The negative skewness is not to be explained as due to lag pebbles, as in the swash-line and backshore, but is probably a result of variability in competency. The foreshore receives the most continuous wash, which eliminates the very fine sand. The competency of ordinary waves is probably sufficient to transport fine sand up and down the foreshore, but is not sufficient to move much coarser material. Occasional waves of greater competency are able to move coarser material, particularly particles of medium sand, up on the foreshore. These particles remain on the foreshore through periods of ordinary wave action and tend to skew the curve of the analysis to the coarser side of the median. It

seems possible that a negative skewness could be achieved on the foreshore through waves of constant uniformity, because the velocity of the up-coming water exceeds that of the backwash, so that two degrees of competency are in sequence all the time. This means that of the sediment transported up the foreshore, only the finer particles could be carried out by the backwash, and a negative skewness would result.

Plunge-line (zone E)—Thirteen samples were collected from the plunge-line zone. In these samples Mdϕ varies from -0.10 to 0.81, and in 12 of the samples is restricted to the range of 0.45 to 0.81. QDϕ varies from 0.23 to 0.92, and in nine of the samples from 0.36 to 0.48. Skqϕ ranges from -0.24 to 0.23 and in 10 of the samples from 0.24 to 0.01.

The plunge-line sediments are the only sediments composed dominantly of coarse and very coarse sand. No secondary maximum is present in any of the samples analyzed, indicating that the sediments are all of the same origin as far as competency is concerned. Collectively, these sediments contain less medium, fine, and very fine sand than the sediments of any other zone.

Sand-Gravel Zone (zone F)—Five samples were taken from patches of sand in the sand-gravel zone. The gravel was not sampled because it was not possible to take the large sample necessary to represent the size distribution present. The cobbles are well washed and occur on the surface in this zone in which the waves erode the bottom. They are thus of lag origin. The sand present in patches on the surface (in contrast to that held between the cobbles) is obviously different in origin from the cobbles.

In the six samples analyzed, Mdϕ ranges from 0.50 to 1.80. QDϕ is almost as variable and is confined to the range of 0.40 to 0.85, and in four of the samples is limited to 0.40 to 0.69. Skqϕ is negative in all the samples but one and ranges from -0.30 to 0.02.

There seems to be a definite relation between the particle size of the sand and he distance from shore. The coarsest sample, 14–3 (Mdϕ .35) was collected 1 meter from the shore; 14–3 (Mdϕ 1.24) was taken at the same time but 2 meters from the shore. Sample 1–2 was collected 1 meter from the shore, but at the southwest margin of the bay where there is no beach and where wave activity is not very great; the latter is indicated by the poorer sorting of this sample (QDϕ 0.69).

The sand in this zone apparently originates partially through lag and partially from backwash. No reason is evident for the concentration of the sand in patches, particularly since it cannot be correlated with changes in the contour of the bottom.

Rippled Sand Zone (zone G)—Seven samples were collected from the rippled sand zone. Mdϕ ranges from 1.10 to 1.45, but in six of the samples is restricted to 1.25 to 1.45. QDϕ ranges from 0.47 to 0.77, and in six of the samples from 0.47 to 0.62. Skqϕ is negative in six of the samples and has a total range of -0.37 to 0.05; Skqϕ in five of the samples varies from -0.02 to -0.17.

The sediments of this zone are probably subjected to less rigorous wave activity than any of the zones thus far described, with the possible exception of the backshore. That some wave action is present is indicated by the wave ripple marks. This lack of selective wash is illustrated by the spread of the curves, particles of every grade from granules to very fine sand being present in this zone. The average value of QDϕ indicates that the spread of the curves between the quartiles is also greater than in the sediments of the other zones, with the exception of the sand-gravel zone. An examination of table 1 shows that only two of the samples (5–7 and 14–4) have a secondary maximum in the size distribution.

The origin of these sediments is not readily seen. At first thought, it might seem that these sands are derived from the shore, and it is possible that the fine and very fine sands are so derived. How-

ever, all the samples analyzed contain coarse sand, very coarse sand, and some granules and it is difficult to imagine these particles being carried out to this zone by undertow currents; some of these coarse particles might be blown out on the ice in the winter and become a part

Zone H—Only two samples were collected from this zone, which consists of dirty sand and plant-covered cobbles showing no effects of wave action. These samples were collected along the west margin of the bay. Mdϕ in these samples is 1.12 and -0.91; QDϕ is 2.02 and 1.57

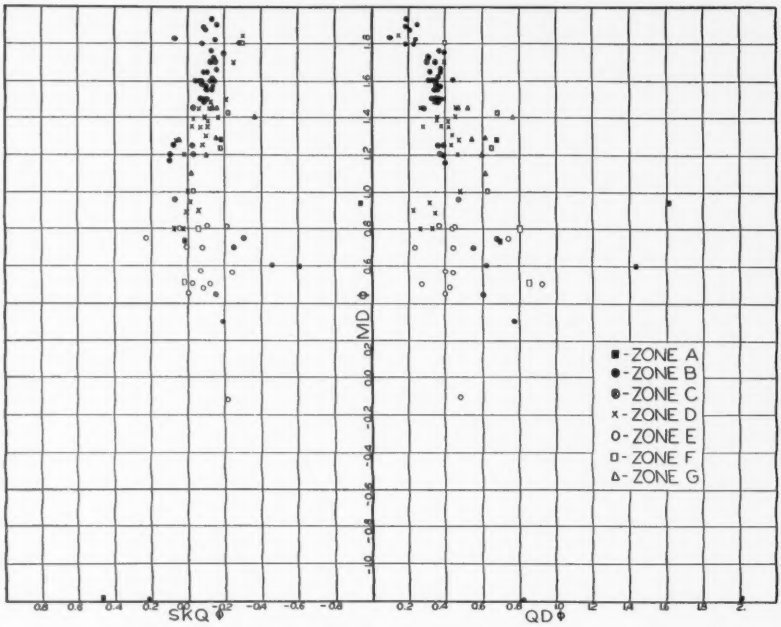

FIG. 3.—A scatter diagram showing the phi median (Mdϕ) diameters plotted against quartile deviation (QDϕ) on the right and phi skewness (Skqϕ) on the left. The samples of the various zones are indicated by the symbols shown on the legend.

of the sediments in that way. However, their occurrence would be irregular and would not produce the nearly symmetrical size distribution found.

It seems more likely that the sediments of these zones are mostly native to their environment and are merely being reworked by the waves producing the ripple marks. Some fine material is probably transported to and from the shore, but the sediments are not greatly modified by this exchange.

and Skqϕ -1.32 and -0.38. These sediments are thus obviously heterogeneous and poorly sorted and show no effect of selective washing.

CHANGES IN POSITION OF THE ZONES

The samples collected by Mr. Rodgers were taken at the same distances on the beach with respect to a standard point, but due to fluctuations in water level and a general increase in width of the beach

throughout the summer, these samples were not taken at the same distances from the water. Comparison of these samples shows the general type of textural change that takes place on a beach at points the same distance from a standard point, and at points the same distance from the water's edge. The number of samples available for such comparison do not warrant a detailed discussion; therefore, the subject is treated briefly and effort made only to show the type of change that takes place.

Samples Taken the Same Distances from a Standard Point.—In general the samples taken on the backshore at the same distance from a standard point show least variation. This is to be expected on this part of the beach, for it is only reached by occasional waves. In five samples collected from one point on the backshore (II-5, III-6, 7–6, 9–6, and 11–1), Mdϕ ranges from 1.57 to 1.72, QDϕ ranges from 0.31 to 0.38, and Skqϕ from −0.14 to −0.03. In four samples (II-7, III-7, 7–7, and 9–7) collected from another point in the backshore, MDϕ ranges from 1.76 to 1.88, QDϕ from 0.21 to 0.37, and Skqϕ from −0.13 to −0.08. These samples, as may be seen in table 1, were collected over a two-week period in early July.

The greatest variation occurs in those sediments of the foreshore, near the plunge-line zone and near the swash-line zone. One set of samples (II-1, III-1, 7–2, and 9–2) taken from the same point record the transfer of this point from the plunge-line zone to the foreshore and then back to the plunge-line zone. In these samples Mdϕ ranges from 0.50 to 1.50, QDϕ from 0.27 to 0.92, and Skqϕ from −0.12 to 0.01. These changes took place in the course of 10 days in early July.

Another set of samples (17–1, 29–1–4, 30–1–4, and 42–1–4) illustrate the change of position of the boundary between the foreshore and swash-line zone. In these samples, Mdϕ varies from 0.30 to 1.40, QDϕ from 0.27 to 0.77, and Skqϕ from −0.18 to 0.07. These samples were collected in three weeks in July and August.

Samples Taken the Same Distances from the Water's Edge.—The change of width of zones may be illustrated by a comparison of samples taken at the same distances from the water's edge. The type of change is the same as that illustrated above, and only three examples are given.

The samples collected near the water's edge show the least variation of the foreshore sediments. In four samples (II-1, III-1, 7–1, and 9–1) taken 5 to 10 centimeters from the water Mdϕ ranges from 0.45 to 0.70, QDϕ from 0.40 to 0.92 and Skqϕ from −0.24 to 0.01.

In three samples (II-1, III-2, and 7–2) collected 30 to 35 centimeters from the water Mdϕ ranges from 0.57 to 1.50, QDϕ from 0.35 to 0.45 and Skqϕ from −0.21 to −0.09. The fine sand (7–2) represents a change of zone from plunge-line to foreshore.

Another set of five samples (II-4, III-4 7–3, 29–1, and 30–1) collected 80–85 centimeters from the water's edge, illustrate the changing position of the swash-line. Four of these samples represent the foreshore sediments and in these Mdϕ ranges from 1.35 to 1.45, QDϕ from 0.35 to 0.47 and Skqϕ from −0.08 to −0.02. The fifth sample (29–1) represents the swash-line, and Mdϕ is 0.45, QDϕ 0.60 and Skqϕ −0.15. These samples were collected over a period of five weeks; samples 29–1 and 30–1 were collected on consecutive days and show the change in position and width of the swash-line zone taking place in one day.

ACCURACY OF SAMPLING

In order to test the accuracy of sampling, eight sets of four samples each were collected; each set of samples was taken at the same time at points the same distance from the water's edge. The analyses of each set of samples was taken at the same time at points the same distance from the water's edge. The analyses of each set of samples agree closely (see table 1, samples 29–1–4, 29–5–8, 30–1–4, 30–5–8, 34–1–4, 34–5–8, 42–1–4, and

42–5–8). The median diameters of the test samples were compared by the probable error method of Krumbein (1934, pp. 204–214). The total observed error in the eight sets varied from 1.8 to 3.8 per cent, and averaged 2.48 per cent. Excluding samples 29–1–4, taken from the swash-line, the average total observed error was 2.27 per cent. The low average total observed error adds considerable significance to the results of the other analyses; differences in texture are thus mainly due to environmental factors and not to sampling errors.

SUMMARY

The studies made of the beach sands at Trout Lake indicate the presence of textural zones paralleling the water's edge. Each of these zones has textural features distinguishing it from other zones; these differences reflect inherent differences in the environment, which should be present in most beaches. These distinguishing textural features of the various zones are summarized briefly:

A. Wave-cut cliff. Texture extremely variable, Mdϕ ranging from -1.32 to 1.28 in the samples analyzed. In general, all grades of sand and gravel are present, although the finer grades of sand are not present in abundance.

B. Backshore. Mdϕ is usually between 1.50 and 1.94, but may be as coarse as 0.75, depending on the amount of lag particles present. An appreciable amount of fine sand is present in this zone, and absent in most of the other zones.

C. Swashline. Mdϕ varies between 0.30 and 0.96, or between 1.20 and 1.70, depending on whether a pebble concentrate is developed. Fine sand is absent, and more coarse sand is found than in the backshore. The sand is coarser than that of the backshore and finer than in the foreshore and plunge-line.

D. Foreshore. Mdϕ is usually confined between 1.20 and 1.50. Pebbles, granules, very coarse sand, and fine sand are not present in this zone.

E. Plunge-line. Mdϕ varies from -0.10 to 0.81. These sediments are the only ones composed dominantly of coarse and very coarse sand. No secondary maximum is present in any of the samples analyzed.

F. Sand-gravel zone. Sediments consist of well-washed cobbles with occasional patches of sand. Mdϕ in the sand ranges from 0.50 to 1.80; the coarseness increases toward the shore.

G. Rippled sand zone. Mdϕ ranges from 1.10 to 1.45. The extreme sizes are present as in the backshore. If the mean values are taken, the sediments of the rippled sand zone are slightly coarser and more poorly sorted than those of the backshore.

H. Zone H. Mdϕ is extremely variable (-0.91 to 1.12) and the sorting is very poor (QDϕ 1.57 and 2.02). The sediments of this zone may be assumed to be unmodified by wave action.

The textural differences of these sediments ought to be found, in a general way at least, in other lacustrine beach sediments, both modern and ancient, and may aid in distinguishing beach deposits from other sediments. The results obtained, although significant, are based on the study of a limited area and thus can be given only provisional general application until further study is made.

The regular and irregular variations of the beach sediments examined point to the necessity of collecting samples with regard to the phase of the environment to which they belong. Samples of modern beaches should not be taken according to a predetermined grid pattern, but should be collected according to the environmental pattern. In this way, textural changes may be found which would be missed entirely if a grid pattern alone were followed. Careful sampling and study of environmental factors will lead to the best interpretation and use of textural variations in an environment as complex and rapidly changing as a beach.

REFERENCES

APFEL, EARL T., *1938*, Phase sampling of sediments: *Jour. Sedimentary Petrology*, vol. 8, pp. 67–69.

EVANS, O. F., *1939*, Sorting and transportation of material in the swash and backwash. *Jour. Sedimentary Petrology*, vol. 9, pp. 28–31.

FRIES, CARL, *1938*, Geology and groundwater of the Trout Lake Region, Vilas County, Wisconsin. *Wisconsin Acad. Sci.* Trans., vol. 31, pp. 305–322.

KRUMBEIN, W. C., *1934*, The probable error method of sampling sediments for mechanical analysis. *Am. Jour. Sci.*, 5th ser., vol. 27, pp. 204–214.

———, *1938*, Local areal variation of beach sands. *Geol. Soc. America Bulletin*, vol. 49, pp. 653–658.

———, *1939*, Recent marine sediments. *Am. Assoc. Petroleum Geologists*, p. 569.

OTTO, GEORGE H., *1938*, The sedimentation unit and its use in field sampling. *Jour. Geology*, vol. 46, pp. 569–582.

THWAITES, F. T., *1929*, Glacial geology of part of Vilas County, Wisconsin. *Wisconsin Acad. Sci.*, Trans., vol. 24, pp. 109–125.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10, NO. 2, PP. 78–90, FIGS. 1–5, TABLES 1–2, AUGUST, 1940

COMPACTION OF LIME MUD AS A CAUSE OF SECONDARY STRUCTURE

RUTH D. TERZAGHI
Cambridge, Massachusetts

ABSTRACT

Calculations based on confined compression tests carried out with lime mud indicate that compaction of this material may produce secondary dips of 60° or more in overlying beds if the material surrounds a relatively incompressible core whose slopes are as steep as 75°. The secondary dips are of course gentler if the slopes of the core are less steep.

A comparison of the data for the lime mud with similar data for a lean and for a fat clay, and with the observed void ratios of deeply buried shale, indicates that the compaction of this lime mud may be at least as great as that of a lean clay, and possibly as great as that of a medium clay.

INTRODUCTION

In articles[1] published within the last two decades a number of investigators have discussed the possibility that dips in sedimentary strata may owe their origin to differential compaction of underlying rocks.

Under compaction are generally included more or less tacitly all volume changes in rock which are due to pressure. The most important of such changes involves the elimination of water from the interstices, generally accompanied by some rearrangement or even granulation of the particles. A large part of this process is completed under an overburden that exerts a pressure of only a few atmospheres on the underlying sediments, but the process probably continues under pressures of several hundreds of atmospheres.

Compaction of shales in the early stages is probably not complicated by other diagenetic processes, and doubtless corresponds fairly closely to laboratory compression tests like those to be described below. However, as Sander (1936) has shown for one formation, the diagenesis of limestone or dolomite may be far more complicated. On the one hand, compaction may include collapse of small cavities, a process whose effects are not included in estimates of compaction based on laboratory tests. On the other hand, in the rock which Sander investigated, solution and chemical deposition took place to such an extent early in the diagenetic process that the results of an ordinary laboratory compression test could not be applied to this particular case. Early stages in the diagenesis of other calcareous sediments may correspond closely to the compaction of lime mud in an oedometer (apparatus for the determination of the compressibility of unconsolidated sediments and soils). Such rocks could probably be identified by a study of thin and polished sections. It is perhaps needless to say that the results of the tests described below can be applied only to such cases.

In addition to the specific acknowledgements made in the text, the writer wishes to take this opportunity of thanking Kirk Bryan, Otto Fröhlich, Bruno Sander and Karl Terzaghi for many valuable criticisms and suggestions.

DIFFERENTIAL COMPACTION IN A REEF STRUCTURE OF THE CHICAGO AREA

The writer's first encounter with the problem was in connection with a study

[1] See Hedberg (1936) for an excellent summary of previous work.

of the abnormally high dips in the Silurian reef structures of the Chicago region (Doggett, 1925). In the stratified, or fore-reef facies of these, as in similar structures in adjacent areas (Cummings and Shrock, 1928), an inclination of 45° is rather common and dips of 30° to 38° may be observed over relatively wide areas. These high dips are puzzling where the strata not closely associated with reefs are, with few exceptions,[2] approximately horizontal. Since the highest inclination observed by A. G. Mayor (1924) on the detrital deposits about reefs now developing in the South Pacific is 30°, it is extremely improbable that any of the Silurian strata of the Chicago area were deposited with as high an inclination as many of them have at present.

Exposures of extent sufficient to give a complete conception of the detailed relationships of the different parts of the reef structures are not common. However, the west wall of the Thornton Quarry in 1925 exposed an excellent section through a small reef. A diagrammatic sketch is given in figure 1. The sudden steepening of the dip of the strata in the immediate vicinity of the reef is striking and unlike anything commonly observed in deposits made in standing water. That differential compaction may produce such structures will be shown in this paper.

Since the writer's study of the reef structures of the Chicago region, Hedberg (1926, 1936) and Athy (1930) have published laboratory and field evidence to indicate that compaction of clay and shale is sufficient to produce secondary structures under appropriate conditions. Similar data relating to calcareous sediments have, however, never been published, and consequently it remained an open question whether such material is sufficiently compressible to produce secondary structures in overlying sediments.

[2] R. T. Chamberlin (1923, pp. 217–218) called attention to an exception in the anticline of Kentland, Ind., which R. R. Shrock (1933) described in detail.

LABORATORY INVESTIGATION

Nature and origin of material tested.—As a first step toward the solution of the problem, it was decided to determine the compressibility of a lime mud (*drewite*) from Andros Island in the Bahama group, very kindly furnished by Prof. R. M. Field of Princeton University and

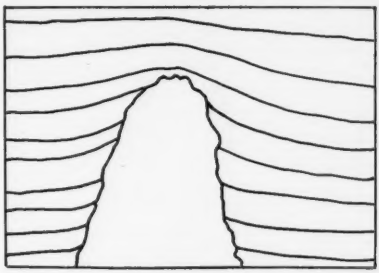

FIG. 1.—Diagrammatic cross-section through a small reef exposed in Thornton (Illinois) quarry (1925). Width of reef at bottom of exposure about 5 meters. The base of the reef was not exposed.

Mr. Maurice Black, now of the University of Cambridge. This material is doubtless much more compressible than calcareous *sand*, and possibly much less compressible than some calcareous *muds*.

Drewite (Field, 1919, 1928) consists chiefly of minute particles of calcium carbonate. The material used in the tests is thought to have been produced by bacterial precipitation (Field and collaborators, 1931). It is largely composed of small needle-shaped grains, presumably aragonite, of which the thickness, as determined by Dr. Leo Jurgenson, varies between 0.005 and 0.0005 mm.; those of approximately 0.002 mm. are the most common. The insoluble residue remaining after boiling in HCl was 1.53 per cent of the material dried at 105°C.[3]

[3] Passages in small type include details which are necessary for a complete understanding of the problems discussed, but not

TABLE 1

	Drewite Andros Is.	Little Belt clay, Denmark	Baden clay Austria
sp.g.	2.63	2.77	2.76
liquid limit	47.8	126–128	45.7–47.6
plastic limit	39.7	33.5–35.8	21.1–22.8
plasticity index	8.1	89.9–93.0	24.6–24.8
% smaller than 0.002	probably <10%	77%	23%

To facilitate future comparisons with other more or less similar materials, Atterberg's limits and other data, in terms of water content in per cent of "dry weight" (105°C.), are given in table 1 along with similar data for two clays with which the lime mud will be compared. As these facts are not of immediate importance to the present problem, they are not discussed further. The meaning of the terms and the methods by which the constants are determined have been described by A. Casagrande (1932). The data for the drewite were furnished by Dr. Jurgenson, and those for the Little Belt and Baden clays (Wiener Tegel) were determined and published by Dr. M. J. Hvorslev (1937).

Experimental procedure.—The tests, known as confined compression tests, were carried out in a consolidation apparatus or oedometer, described by K. Terzaghi (1931a, pp. 555–557 and 1931b, p. 70). An improved type of this apparatus was described by Rutledge (1935).

The data obtained from the consolidation test are the basis for a void-ratio-pressure diagram like those presented in figures 2 and 3. The term *void ratio* refers to the ratio between the volume of voids and that of the solid substance. For problems involving compaction this is a more convenient quantity than porosity, since the void ratio is a variable given in terms of a constant (the volume of solids), whereas the porosity is a variable given in terms of another variable, the total volume.

essential for a general conception of the methods upon which the conclusions were based.

Experimental data.[4]—If the relationship between the void ratio e and the logarithm of the pressure p is represented graphically (see fig. 3) the resulting curve is generally nearly a straight line, as expressed by the equation:

$$e = e_c - C \ln p \qquad (I)$$

[4] The following symbols will be used:
b = radius of buried hill or reef ("core" of structure; see fig. 4).
c_f = final closure.
c_o = original closure.
C = compression index obtained from a consolidation test of a sample in a disturbed state.
C_E = expansion index corresponding to C.
d = height of buried hill or reef.
e = void ratio, i.e. ratio of volume of voids to volume of solid.
e_o = average original void ratio of a deposit.
e_c = void ratio corresponding to 1.0 kg. per sq. cm. obtained from a consolidation test of a sample in the disturbed state.
e_E = void ratio corresponding to 1.0 kg. per sq. cm. obtained when material previously consolidated under a specified pressure is allowed to expand.
e_f = final void ratio of a deposit after compaction under an overburden.
$\Delta e = e_o - e_f$.
H = original thickness of deposit.
ln = natural logarithm.
p = pressure, generally given in kg. per sq. cm.
p_b = pressure at bottom of a sedime ntary deposit.
p_t = pressure at top of a sedimentary deposit, equal to zero in special case under consideration here.
α = angle of slope of surface of buried hill.
β = original dip.
γ_w = weight of one cu. cm. of sea water, about 1.02 gm.
γ = average weight of one cu. cm. of the constituent minerals of a sediment.
γ' = average weight of one cu. cm. of the constituent minerals under sea water = $\gamma - \gamma_w$.
ϕ = final dip.

in which e_e and C are constants characteristic of the material and *ln* denotes natural logarithm (K. Terzaghi 1925, p. 82). The swelling process may be expressed by an analogous equation

$$e = e_E - C_E \ln p. \qquad \text{(II)}$$

Athy (1930) showed independently that the relation between maximum depth of burial and the porosity, or the bulk density, of sedimentary rocks may also be represented by exponential equations. That Athy's equations are practically identical in content with equation (I) is indicated by figure 3*b* which represents the results of a recomputation of Athy's data on bulk density and depth of burial (averages, Athy's fig. 2, 1930) in terms of pressure and void ratio. The pressure is plotted on a logarithmic scale. The compression constant C of this curve is 0.21, corresponding to a clay of approximately average compressibility.

The range of pressure for which equations (I) and (II) are valid varies with the nature of the sediment and to a certain extent with the initial void ratio. The compression tests on lime mud, described in this article, indicate that equation (I) is strictly valid for this material only for pressures of less than a few atmospheres, but it is approximately valid for pressures at least as great as 8 atmospheres. Tests carried out by J. van Krogh (1923, cited by Terzaghi, 1929, p. 340) on Norwegian clays indicated that, for the materials tested, equation (I) is valid up to a critical pressure of 80 to 100 atmospheres. Subjected to higher pressures, the clay particles apparently began to flow. Van Krogh found that the water content of lean clays was reduced to zero under pressures of about 160 atmospheres, whereas that of fat clays was not completely eliminated until pressures of about 340 atmospheres had been reached. On the other hand, Athy's data concerning change of porosity with depth, corresponding to pressures between 60 and 170 kg. per sq. cm., agree very well with equation (I), as indicated by figure 3*b*. It is, of course, not certain whether the average material represented by this curve would be characterized by the same "constants" under lower pressures. For a very fat clay, the discrepancy between the observed void ratio-pressure relationship and equation (I) is conspicuous even at low pressures, if the initial water content is notably above that corresponding to the liquid limit. The compression curve of the Little Belt clay, shown in figure 3*a*, is a striking example of this.

The values of the "constants" vary somewhat with the conditions of the experiment. Thus for any given pressure, the corresponding void ratio is higher if the initial void ratio is high than if it is comparatively low, whereas the curve for many materials is somewhat steeper for large load increments than for small ones.

Two confined compression tests have been carried out on lime mud from Andros Island. One, in which the highest pressure used was 3.2 kg. per sq. cm., was performed by Dr. A. Casagrande, and the other, in which pressures up to 8.5 kg. per sq. cm., were employed, was made by the writer. The two tests are represented by curves *I* and *II* respectively, in figures 2 and 3*a*. As the two curves were determined under somewhat different conditions, they do not coincide. The high initial water content of the sample used in the second test was chosen as probably representing the initial natural water content of the material. The constants for the two curves are as follows:

	p	C	e_e	C_E	e_E
I "Standard" test	0.85–3.2	0.101	1.03	0.005	0.92
II "High water-content" test	0.05–5.0	0.147	1.44		
	5.0 –8.5	0.20	1.52[5]	0.011	1.13

[5] Extrapolated.

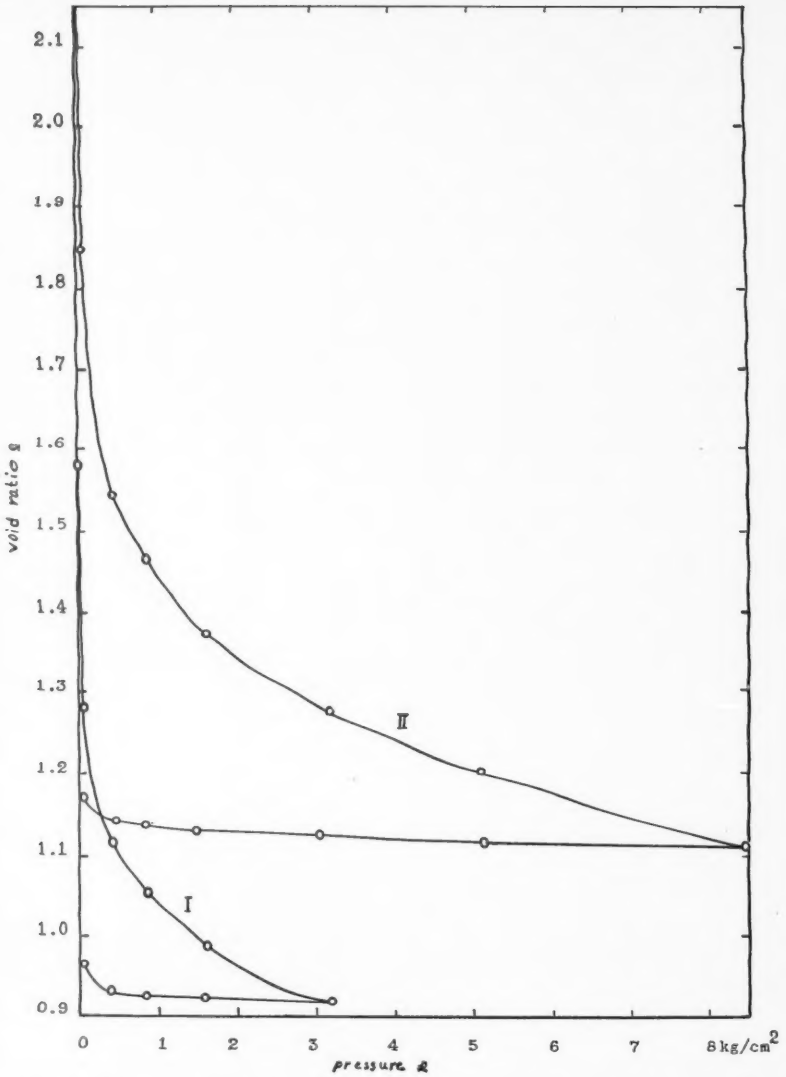

FIG. 2.—Two void ratio-pressure diagrams for specimens of drewite which were identical except that the initial void ratio of that used for test I was 1.58 whereas that of the specimen of test II was 2.28.

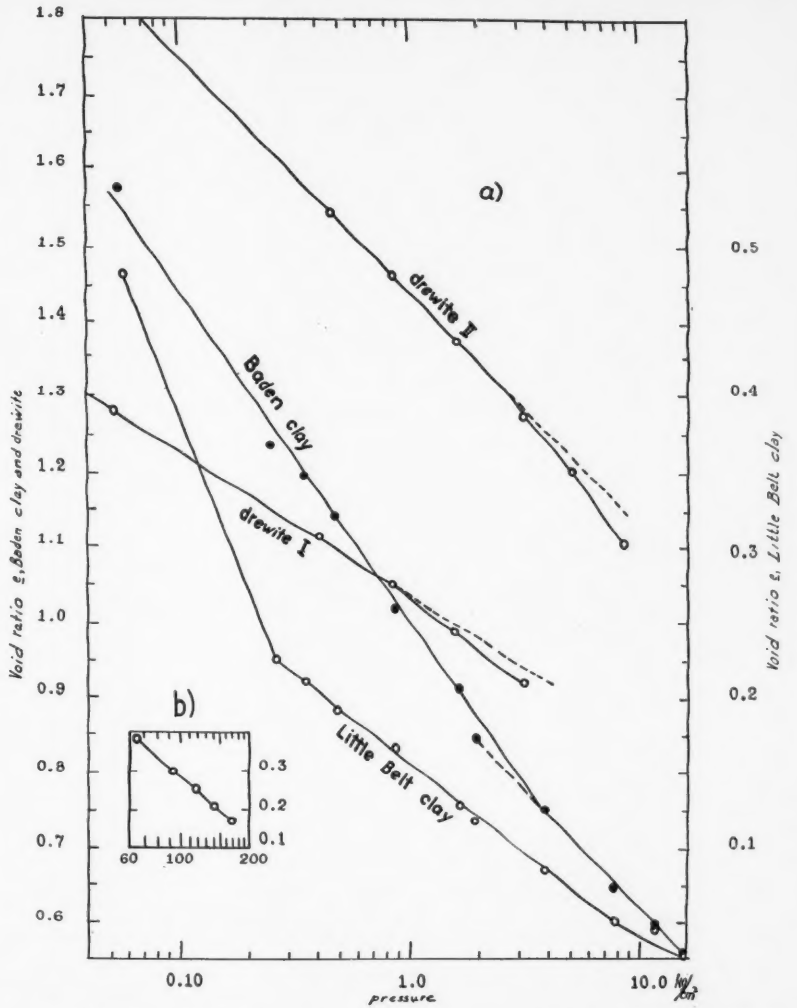

FIG. 3*a*.—The relation between void ratio (e) and the logarithm of the pressure for drewite, Baden clay and Little Belt clay. The void ratio scale for the first two is that extending from 0.6 to 1.8 at the left; that for the Little Belt clay extends from 0.25 to 5.0 at the right. The pressure (p) is given in kg. per sq. cm.

FIG. 3*b*.—The relation between average void ratio of a series of shales and the logarithm of the pressure exerted by the overburden. Computed from the data given by Athy (1930, fig. 2).

When the two curves are plotted on semi-logarithmic co-ordinates, as in figure 3*a*, they both show a striking feature which has seldom if ever been observed in consolidation curves for ordinary sands or clays under low pressures. Whereas the slopes of such curves are constant or decrease slightly with increasing pressure, the slopes of the curves shown in figure 3*a* increase progressively after the pressure has exceeded a certain value whose magnitude probably depends in part on the initial void ratio. This abnormal steepening suggests that certain favorably oriented grains, probably the needle-like aragonite crystals in particular, may have been sheared or broken by the pressure transmitted by their neighbors.

APPLICATION OF EXPERIMENTAL DATA

Comparison of compressibility of drewite with that of clay.—Although it would be premature to make an unqualified statement regarding average properties of sediments and soils, an inspection of the files in the soils laboratories of the Technical University of Vienna and of Harvard University, which contain data concerning specimens from various parts of the world, may serve to give a rough idea of the range of compressibility of sediments which, in a more or less consolidated state, would be designated as shale. In 1937, the files of the Vienna laboratory contained the results of compression tests on about 20 such sediments. Of these, 15 have a compression index from 0.10 to 0.17 as determined by standard tests whereas only five have an index greater than 0.17. Data for some 24 consolidation tests on "clayey" sediments are available in the files of the soils laboratory of Harvard University. Of these, 12 were made on sediments whose compression index is between 0.10 and 0.17 and 12 represented sediments having a compression index greater than 0.17. As a first approximation, we may conclude that the compression index of the average "clayey" sediment is probably between 0.15 and 0.20.

Since lime mud from Andros Island has a compression index of 0.103 as determined by the standard test, it will be seen that its compressibility under low pressure is comparable to that of the less compressible of the cohesive or "clayey" sediments. However, as noted above, granulation or deformation of the calcite or aragonite particles appears to begin under moderate pressure, and it seems likely that this factor may increase the compression index for pressures as high as 50 to 100 kg. per sq. cm. to 0.25 or more, which is at least as high as that of an average clay.

In order to facilitate the comparison between drewite and a "lean," only moderately compressible clay on the one hand, and a "fat" or highly compressible clay on the other, a representative of each type was selected for a special "high water-content" compression test. The Atterberg limits and other data for these materials are given in table 1, and the pressure-void-ratio diagrams in figure 3*a*.

Calculation of closure and dip.—The next step is to develop a quantitative method of estimating the amount of dip which may be produced in overlying strata by the compaction of sediments whose compressibility at low pressures, as well as original and final void ratios, are known or can be estimated with sufficient accuracy. On the basis of consolidation tests, we first calculate the average void ratio of the column of sediments whose compaction is supposed to have produced an inclination of overlying strata. The relation between depth of deposit H in cm. and the pressure in gm. per sq. cm. at the bottom of the deposit, p_b, is given by the equation:

$$H=\frac{p_b}{\gamma'}(C-C\ ln\ p_b+e_c+1). \qquad \text{(III)}$$

The derivations of this and of the following equations are given below in small type. The numbers after the equations in

the following paragraphs correspond to those used in the derivations of the equations.

Since it is not possible to solve equation (III) directly for p_b, a few points on the $p_b:H$ curve may be computed, and the desired values determined by interpolation. The average void ratio e_a of a deposit in which the pressure at the top is zero and that at the bottom is p_b may be calculated from the following equation:

$$e_a = e_c + C(1 - ln\ p_b). \qquad \text{(VII)}$$

The average void ratio may also be determined graphically by dividing the curve lying between the ordinates p_b and p_t into segments each of which represents the same fraction of $(p_b - p_t)$, determining the midpoint of each segment and averaging the corresponding values of the void ratio e. Next, we estimate the final void ratio which the material has after the column of sediments deposited upon it is complete. In some cases this might be approximated from laboratory tests, but in others it will be preferable to base the estimate on data for actual limestones or shales, as the case may be.

The relation between the final closure c_f (see fig. 4), the original closure c_o, the depth of the deposit H, the original average void ratio e_a and the final void ratio e_f is:

$$c_f = c_o + H\frac{(e_a - e_f)}{1 + e_a}.$$

The relation between $\tan \phi$ (final angle of dip) $\tan \alpha$ (angle of slope of surface of buried hill), and $\tan \beta$ (angle of original dip of sediments) is:

$$\tan \phi = \tan \beta \frac{(e_f + 1)}{e_a + 1} + \tan \alpha \frac{(e_a - e_f)}{e_a + 1}. \qquad \text{(IX)}$$

In order to derive the equations given above, we first determine the relation between the thickness of the deposit and the pressure at the bottom. If the pores are filled with water not under capillary tension, the latter is equal to the total weight of solid matter contained in a column of unit cross-section less the weight of the water displaced by the sediment. As recent experiments (K. Terzaghi, 1936) have shown, this statement is valid even for extremely fine sediments immersed in water, since hydrostatic uplift is practically 100 per cent effective even in such material. Hence the change of pressure with infinitesimal change of depth is:

$$\frac{dp_b}{dH} = \frac{\gamma'}{e + 1}.$$

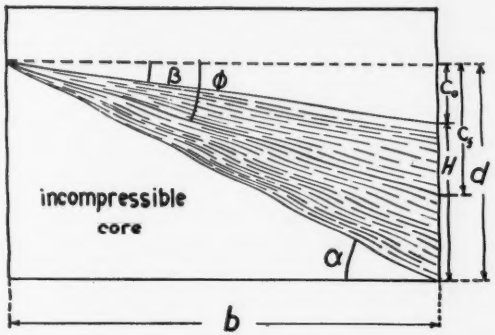

FIG. 4.—Diagram illustrating secondary structure due to differential compaction. α is the angle of slope of the core, β is the original angle of dip of an index bed underlain by compressible sediments, and ϕ is the angle of dip of the same bed after compaction of the underlying sediments.

Since we know e as a function of p (I) but not of H, we write,

$$\frac{dH}{dp_b}=\frac{e+1}{\gamma'}=\frac{1}{\gamma'}(e_c-C\ ln\ p_b+1),$$

from which we obtain,

$$H=\frac{1}{\gamma'}\int(e_c-C\ ln\ p_b+1)dp_b$$

$$=\frac{p_b}{\gamma'}(C-C\ ln\ p_b+e_c+1)+K. \quad \text{(III)}$$

For the case now under consideration, $H=0$ when $p_b=0$, therefore $K=0$. If the depth H of the deposit is expressed in centimeters, the pressure is in gm. per sq. cm.

The next step is to determine the average void ratio of the deposit, i.e., the void ratio which the deposit would have if it were homogeneous. In order to do this, we imagine that the deposit is divided into any definite number of horizontal layers whose thickness varies from top to bottom of the deposit in such a way that all contain the same amount of solid material. The amount of pressure exerted by each layer on those below it, is termed Δp. Within any one layer, the total volume of solid matter in a vertical column of unit cross-section is $\Delta p/\gamma'$. The total volume of voids of such a unit column is the average void ratio of the layer in question, multiplied by the total volume of solids in the same unit column. The total volume of voids per unit of cross-section of the entire deposit is:

$$e_a\frac{p_b}{\gamma'}=\Sigma\left[e\frac{\Delta p}{\gamma'}\right]. \quad \text{(IV)}$$

Such layers might be represented in the void ratio-pressure diagram (figure 2) by vertical strips of equal width extending from the pressure axis to the compression curve between the ordinates for $p=p_t$ and $p=p_b$. Their combined width is equal to p_b-p_t or, since p_t equals zero, simply to p_b. The sum of the areas of such strips is:

$$A=\Sigma[e\Delta p]. \quad \text{(V)}$$

This area may be evaluated as follows:

$$\frac{dA}{dp}=e_c-C\ ln\ p$$

$$A=\int_{p_t}^{p_b}(e_c-C\ ln\ p)dp$$

$$=\left[p(e_c+C-C\ ln\ p)\right]_{p_t}^{p_b}. \quad \text{(VI)}$$

Combining equations (IV), (V) and (VI), we obtain, for p_t equal to zero, the expressions:

$$e_a\frac{p_b}{\gamma'}=\frac{A}{\gamma'}=\frac{p_b}{\gamma'}[e_c+C(1-ln\ p_b)]$$

and

$$e_a=e_c+C(1-ln\ p_b). \quad \text{(VII)}$$

Having estimated the difference between the original and the final void ratios, we proceed to determine the amount of closure or of dip which may be produced under various conditions as a result of differential compaction involving the sediment investigated. Figure 4 represents the problem of such secondary structures reduced to the simplest terms. The horizontal distance from the crest of the buried hill to the foot is b, the height of the hill is d and c_o is the original closure, i.e., the difference between the height d of the hill and the maximum thickness H of the deposit when the top of the hill is just covered. c_f is the final or total closure. The angle of inclination of the surface of the core is α. β is the angle of dip of the uppermost of the sedimentary strata at the time of deposition. After complete consolidation of the underlying strata, the lowest stratum passing over the crest of the hill has an average angle of inclination of ϕ. This angle does not correspond exactly to an actual dip, as the more detailed discussion given below will show, but is the angle whose tangent is equal to c_f/b. The average void ratio of the deposit consolidated under its own weight is e_a and e_f is the void ratio after consolidation under an overburden.

Assuming that the secondary structure is due to differential compaction alone and that faulting or slipping has not complicated the situation, the final or total closure is:

$$c_f=c_o+\frac{H(e_a-e_f)}{1+e_a}. \quad \text{(VIII)}$$

On the simplifying assumption that the dip is uniform in any given stratum, we have,

$$\tan\phi=\frac{c_o}{b}+\frac{H(e_a-e_f)}{b(1+e_a)}.$$

This may be expressed in the more general terms of the geometrical relations involved, which are independent of the dimensions of the core, as follows:

$$\tan\phi = \frac{c_o + (d-c_o)\dfrac{e_a - e_f}{e_a+1}}{b} = \frac{c_o(e_f+1)}{b(e_a+1)} + \frac{d(e_a-e_f)}{b(e_a+1)} = \tan\beta\frac{(e_f+1)}{e_a+1} + \tan\alpha\frac{(e_a-e_f)}{e_a+1}. \quad \text{(IX)}$$

Table 2 gives the results of calculations of actual dips which may be produced in a bed underlain by drewite and passing over the top of a relatively incompressible core 10 meters high, having a surface sloping at any one of the angles indicated in the table. It will be noted that the height of the hill, or core, does not have a very marked effect on the amount of dip, and that a moderate initial dip does not significantly increase the final dip. The secondary dip does, on the other hand, increase rapidly with the slope of the surface of the core.

TABLE 2. *Dips produced by compaction of drewite*

e_f*	α	ϕ if $\beta=0$ & $d=10$m	ϕ if $\beta=10°$ & $d=10$m	ϕ if $\beta=0$ & $d=100$m	ϕ if $\beta=10°$ & $d=100$m
0.11	30°	18°	22°	17°	21°
	45°	30°	33°	27°	31°
	60°	45°	47°	42°	44°
	75°	65°	66°	63°	64°
0.33	30°	16°	21°	13°	19°
	45°	26°	30°	23°	27°
	60°	41°	43°	36°	39°
	75°	62°	62°	58°	59°

* e_f = final void ratio, α = slope of surface of core, β = original dip of strata, d = height of "core," ϕ = final dip of strata. (See fig. 4.)

Variations in dip.—For given values of the angle of slope of the core and of the original angle of dip of the sediments, the amount of dip produced by differential compaction decreases as the height of the hill, or core, increases, since the average original void ratio is larger for a thin deposit of sediments than for a thick one.

The effect of the height of a buried hill on the final angle of dip leads to a more detailed consideration of the form of structures produced by differential compaction. In a limited zone within a foot or so of a core, the final angle of dip is higher than the average calculated for the whole structure, since the original thickness of that part of the deposit under consideration is smaller. In other words, the trace of any bed on a vertical plane parallel to the direction of dip is concave upwards. The degree of concavity, as shown in the next paragraph, depends on several local conditions.

Insofar as variations in dip with distance from the core are not determined by variations in the sediment, primary dip, slope of core or other factors not evaluated in the above discussion of the ideal case, the magnitude of these variations in dip depends on the relative magnitude of the variations in the quantity $(e_a - e_f)$, and these depend on the variations in the original void ratio of the section involved and on the relative importance of the compression which takes place under the overburden. If the latter is great, the relative differences between the original void ratios of adjacent sections are unimportant in comparison to it, and as a consequence, the variations in the amount of secondary dip produced in any one stratum are slight.

If the slopes of a core are steep, the original attitude of the strata nearly horizontal, the material highly compressible and the final overburden not too great, the variation in the angle of dip

may be appreciable. In figure 5 the solid line shows the final position of an originally horizontal index stratum passing over the top of an incompressible core whose slopes dip at an angle of 68° on the assumption that the material has the compressibility of the Andros Island lime mud and a final void ratio of 1.0 (50 per cent porosity). The dotted line indicates the final position of a similar bed whose initial dip was 7°. It will be noted that the trace of the index bed under these circumstances is only slightly concave. If compression continues until the material has a void ratio of 0.11, corresponding to 10 per cent porosity, the trace of the index bed is nearly a straight line, even though it was originally horizontal, as shown by the dash-dotted line in figure 5. (The obtuse angle in the line representing the index bed would, of course, be replaced in nature by a smooth curve.) It thus appears that a "concave" structure may be produced by differential compaction under certain circumstances, but this type of structure is by no means an inevitable consequence of differential compaction.

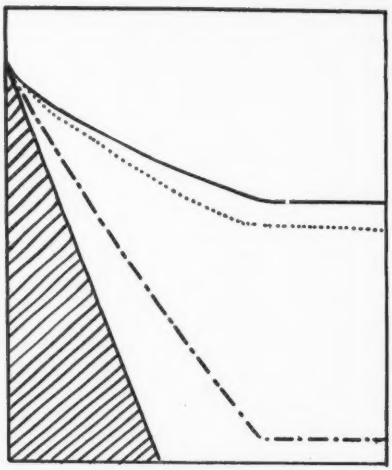

FIG. 5.—Position of an index bed passing over the crest of a hill, after compaction of the underlying drewite. The hill is 10 meters high, but only the upper 6 meters of the hill are shown. The full drawn curve indicates the final position of an originally horizontal bed if the underlying drewite has a final void ratio of 1. The dash dotted line shows the final position of the same bed if the final void ratio of the drewite is 0.14. The dotted line shows the final position of an index bed whose original dip was seven degrees if the underlying drewite has a final void ratio of 1.

SUMMARY

Structures associated with the Silurian reefs of northern Illinois and adjacent states are among those whose origin is attributed to the compaction of calcareous sediments. In these structures an inclination of 45° or more is rather common and dips of 30° to 40° may be observed over relatively wide areas.

The present investigation was undertaken in order to determine whether the compressibility of a typical lime mud is sufficiently high to account for dips as great as those observed in these and in other structures. It is emphasized that

the results of the tests are applicable only to sediments whose mechanical consolidation has not been interrupted or prevented by chemical deposition in the interstices.

Confined compression tests carried out with various types of unconsolidated sediments show that there is commonly an approximately linear relationship between the void ratio and the logarithm of the pressure (see fig. 3). The steepness of the line, indicated by the compression index C, is a measure of the compressibility of the material. That of the lime mud from Andros Island is approximately equal to the compressibility of the "leaner" or less compressible clayey sediments.

However, experimental evidence indicates that the compression index of lime mud under pressures greater than a few kg. per sq. cm. increases with the pressure, in contrast to that of many clays, which decreases with increasing pressure. It seems likely that the compressibility of lime mud under pressures of 50 to 100 kg. per sq. cm. may be equal to that of the average clayey sediment.

Assuming that the increase in the compression index with increasing pressure is such that compaction alone decreases the porosity to a final value of 25 per cent, (this corresponds to a void ratio of 0.33) and that the surface of the "core" or reef slopes is at an angle of 75°, the angle of dip of the beds immediately overlying such a reef would be about 60°. (Data for other cases are given in table 2.)

In any one structure, particularly in the immediate vicinity of a "core," the angle of dip produced by differential compaction may be expected to decrease with increasing distance from the core, and under certain circumstances the trace of the beds on a vertical plane may be conspicuously concave upward. The fore-reef of a small Silurian reef of the Chicago area (see fig. 1) appears to present an example of this type of structure.

REFERENCES

ATHY, L. F., *1930*, Density, porosity and compaction of sedimentary rocks: *Am. Assoc. Petroleum Geologists, Bull.*, vol. 14, pp. 1–24.

CASAGRANDE, A., *1932*, Research on the Atterberg limits of soils: *Public Roads*, vol. 13, pp. 121–130.

CHAMBERLIN, R. T., *1923*, On the crustal shortening of the Colorado Rockies: *Am. Jour. Sci.*, vol. VI, pp. 215–221.

CUMMINGS, E. R., and SHROCK, R. R., *1928*, "Niagaran coral reefs of Indiana and adjacent states: *Geol. Soc. America, Bull.*, Vol. 39, pp. 579–620.

DOGGETT, R. A., *1925, Origin of the abnormally steep dips in the Niagaran reefs of the Chicago region:* Unpublished master's thesis, University of Chicago.

FIELD, R. M., *1919*, Investigations regarding the calcium carbonate oozes at Tortugas, and the beach rock at Loggerhead Key: *Yearbook* 18, *Carnegie Inst. Washington*, pp. 197–198.

———, *1928*, The Great Bahama Bank, studies in marine carbonate sediments. *Am. Jour. Sci.*, vol. 16, pp. 239–246.

FIELD, R. M., and Collaborators, *1931*, Geology of the Bahamas: *Geol. Soc. America Bull.*, vol. 42, pp. 759–784.

HEDBERG, H. D., *1926*, Effect of gravitational compaction on the structure of sedimentary rocks: *Bull. Am. Assoc. Petroleum Geologists*, vol. 10, pp. 1035–1072.

———, *1936*, "The gravitational compaction of clays and shales: *Am. Jour. Sci.*, vol. 31, pp. 241–287.

HVORSLEV, M. J., *1937*, Ueber die Festigkeitseigenschaften gestörter, bindiger Böden, with an abstract in English: *Danmarks Naturvidenskabelige Samfund*, Ingeniorvidenskabelige, Skrifter A. No. 45.

KROGH, J. VAN, *1923, Undersokelser over Norske Lerer:* Staatens Rastofkomite. III. Christiania.

MAYOR, A. G., *1924*, Structure of the Samoan reefs: *Carnegie Institute of Washington*, vol. 19, Pub. no. 340, pp. 1–25.

RUTLEDGE, P. C., *1935*, Recent developments in soil testing apparatus: *Jour. Boston Soc. Civil Engineers*, vol. 22, pp. 223–252.

SANDER, B., *1936*, Beiträge zur Kenntniss der Anlagerungsgefüge: *Mineralog. u. Petrog. Mitt.* vol. 48, pp. 27–139 and 141–209.

SHROCK, R. R., *1933*, The Kentland area of disturbed Ordovician rocks in northwestern Indiana: *Jour. Geology*, vol. 41, pp. 337–370.

TERZAGHI, K., *1925*, *Erdbaumechanik*, Vienna.

———, *1929*, (with K. Redlich and R. Kampe) *Ingenieur Geologie*, Vienna.

———, *1931a*, Festigkeitseigenschaften der Schüttungen, Sedimente und Gele: in Auerbach, F. und Hort, W., *Technische Physik der Festen Körper*, 1931: Leipzig, vol. 4, pt. 2, pp. 513–578.

———, *1931b*, The influence of elasticity and permeability on the swelling of two-phase systems: in Alexander, Jerome, *Colloid Chemistry*, 1931, New York, pp. 65–88.

———, *1936*, Simple tests determine hydrostatic uplift: *Engineering News-Record*, vol. 116, pp. 872–875.

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SUGGESTIONS FOR THE FACILITATION OF GRAIN COUNT WITH THE PETROGRAPHIC MICROSCOPE

WILLIAM A. WHITE
Maracaibo, Venezuela

ABSTRACT

A new cross-hair arrangement and a spring activated stage-lock are used to eliminate observations made in peripheral parts of the field of vision.

In the quantitative study of particulate mineral aggregates, it is a common practice to make grain counts of the several constituent species. For this task petrographers usually use a polarizing microscope equipped with mechanical stage and cross-air ocular. This equipment may be employed in several ways, but one of the common procedures is to arrange the cross-hairs normal to and parallel with the direction of traverse and count all grains as they cross the hair lying normal to the traverse course. In employing this procedure the writer has encountered certain difficulties. This paper offers suggestions for obviating them.

Figure 1 shows diagrammatically a microscope field across which a traverse is being made from top to bottom. Three mineral grains are represented, together with conventional cross-hairs oriented in vertical and horizontal directions, respectively parallel with and normal to the direction of traverse.

It will be noted that the three mineral grains cross the circle of vision on chords of highly unequal length. Grain 1 traverses a chord equal to the line *A-A'*. It crosses the field almost diametrically. Grain 2 traverses a shorter chord equal to *B-B'*. Grain 3 traverses a very much shorter chord equal to *C-C'* which is little more than tangential to the field of vision. Furthermore, grain 3 is never wholly within the field of vision. It is evident that grains 1 and 2 will impress their presence upon the observer much more readily than grain 3, for they will be entirely within the field of vision and will be there several times as long.

It has been the observation of the writer that the eye tends to appraise the arrangement and identity of grains before they reach the cross-hair on which the counting is done. Certainly an appreciable portion of the field forms the theatre in which grains are scrutinized, and probably very few are counted at the precise moment they cross the hair.

It would seem plausible, then, that the chance of any particular grain being identified correctly and counted will vary in some direct manner with the length of its path across the field of view. Grains crossing the field well in toward the center will receive adequate attention whereas those crossing on short paths close to the periphery may slip by unseen or receive, at best, a hasty diagnosis subject to the errors of quick judgment. Grains having an index of refraction nearly the same as that of the mounting medium are especially apt to pass unnoticed.

The obvious reason for these difficulties is that the field of vision is circular. Correspondingly the apparent solution of the problem is to make the field at least partially rectilinear.

To attain this end several expedients were tried. The most successful of them is shown by figure 2. Instead of the two conventional cross-hairs, three are used. Two of these occupy the positions of equal and parallel chords oriented vertically. The third occupies the position of a diameter perpendicular to the other two.

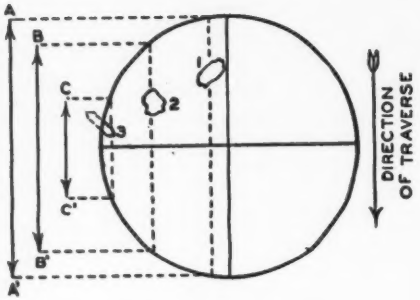


FIG. 1

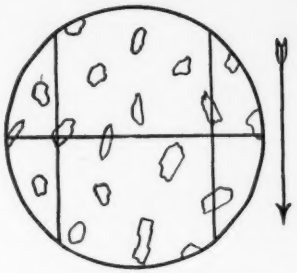


FIG. 2

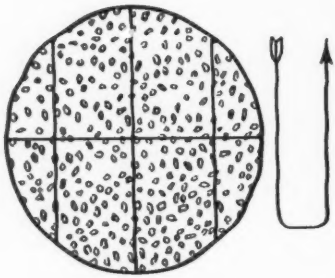


FIG. 3

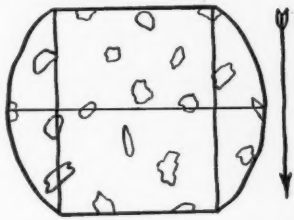
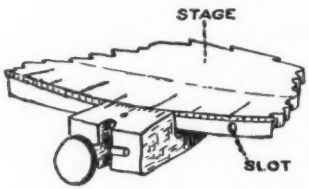


FIG. 4



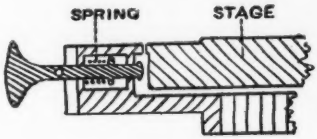


FIG. 5

FIGS. 1–5

The most satisfactory spacing of the two vertical hairs is that which allows them to intersect the diametric hair at points about one-third of the distance from the periphery of the field to the center. The direction of traverse is parallel with the two vertical hairs which serve as boundaries or outer limits for the utilized field. Grains are counted as they cross the diametric or horizontal hair, but only those grains are counted that lie between the two vertical hairs or are cut by *one* of them. By not counting those grains cut by the other vertical hair, it is possible to make consecutive traverses that are precisely contiguous. When the mechanical stage is to be set on a new traverse, one vertical hair is moved horizontally to the exact position vacated by the other.

Through the use of this ocular arrangement, all grains counted are wholly visible in a central and achromatic part of the field for a relatively long and nearly equal period of time.

The diametric hair may be used as a reference line for the measurement of extinction angles. Nevertheless, it may be advisable to include a fourth or vertical diametric hair as shown in figure 3. This will serve the additional purpose of dividing the field so that two traverses (descending and ascending) may be made when a low powered objective is used, or when grains are closely spaced.

In figure 4, a refinement is suggested which is of dubious value. The upper and lower parts of the field are blocked out opaquely to make the utilized field of vision wholly rectilinear, and to give equal paths across it to all grains counted. By virtue of this equality of path they may make equal claims upon the perception of the observer.

In order that best results may be obtained from traverses, made with either the ocular arrangement described here or the conventional cross-hair arrangement, it is necessary that the direction of motion of the slide remain normal to the hair on which the counting is done. So long as the stage is not rotated this relationship is easily maintained with the usual stage-lock. However, in counting most mineral aggregates, it is necessary to rotate the stage frequently in order that extinction angles and interference colors may be observed. Although hand and eye rapidly become adept in preserving a general accuracy of orientation of the stage, the writer has found it preferable to use the spring catch depicted in figure 5. A slot in the periphery of the stage marks the position of proper orientation, and the shoe of the catch snaps into it automatically as the stage is rotated. The activating spring is weak enough that the stage can easily be turned against its pressure. The design of the catch is such that it can be inactivated by a quarter turn of the button, leaving the stage unrestricted.

The writer desires to acknowledge indebtedness to Dr. Gordon Rittenhouse for helpful criticism of the manuscript.

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A NEW CENTRIFUGE TUBE FOR HEAVY MINERAL SEPARATION*

W. E. BERTHOLF, JR.
Soil Conservation Service, Chicago, Illinois

Various types of centrifuge tubes are now used for heavy mineral separations, but no type known to the writer is entirely satisfactory. In plain tubes, the separated fractions must be removed by decantation or with a special pipette. Consequently contamination is a constant problem. Tubes having valves are not constructed so that the light and heavy fractions can be removed simultaneously to individual filter papers. In addition, the valves may leak during the centrifuging process. Many types of tubes, moreover, require an excessive amount of wash liquid to remove the adhering grains.

To eliminate these undesirable characteristics, a tube was designed that combines the desirable qualities of the Müller (Müller, 1932) tube and some new features. This tube has been used successfully for more than 100 heavy mineral separations. The tube (fig. 1) has six parts, an outer tube with flanged rim, an inner tube with flanged rim and constricted lower opening, a glass stopper made to fit the lower opening in the inner tube, a one-hole cork stopper, a metal collar, and a wire spring. The downward (outward) force exerted on the inner tube, during centrifuging, is counterbalanced by thickening the lower part of the tube. The cork stopper is held in place with the wire spring that clamps into the metal collar, and has the dual purpose of holding the glass stopper and preventing the inner tube from floating in the heavy liquid. Inasmuch as the flange on the outer glass tube is not strong enough to support the weight of the apparatus during centrifuging, breakage is prevented by supporting the tube on a rubber cushion inserted in the bottom of the metal sling tube.

The heavy mineral separation is made as follows: The assembled tube is filled with heavy liquid until the inner tube begins to float. The sample, 10 grams or less in weight, is added and stirred to remove air. The glass stopper is suspended as shown in figure 1 and the cork stopper clamped in place. The tube is then inserted in the metal sling tube of the centrifuge and swung for five minutes at approximately 1,800 r.p.m. If but one tube is used, it must be counterbalanced in the centrifuge with lead shot or other suitable material. When two or more tubes are used, the total weight of the tube, heavy liquid, and sample must be the same for each.

To recover the light fraction, the inner tube is sealed off by pushing the glass stopped into the constricted opening of the inner tube. This tube is then transferred to a funnel containing a filter paper, and the contents allowed to drain into it. The heavy fraction is obtained by draining the outer tube into a second filter paper. By using a wash bottle and suitable wash liquid, grains adhering to the apparatus can be washed onto the filter papers.

REFERENCE

MÜLLER, H., *1932, Zentralbl. f. Min., Geol. u Pal.*, Abt. A, pp. 90–91.

* Published with permission of the Soil Conservation Service, U. S. Dept. of Agriculture.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 10. NO. 2, PP. 95–96, TABLE 1, AUGUST, 1940

NOTES ON LIMIT OF SEDIMENT CONCENTRATION

E. W. LANE
University of Iowa, Iowa City, Iowa

Sediment concentration in suspension in streams has at times surprisingly high values. The greatest concentrations no doubt occur in the mud flows which sometimes take place in steep regions due to land slides, or extremely intense rainfalls. On very steep watersheds, the sediment and water become mixed into a fluid mass and flow down the steep streams in much the same manner as concrete flows when being placed in a structure. Judging from the quantity of water required to make concrete flow readily, the quantity of water in such a mass may be as little as 10 per cent. The material in such a flow, however, can hardly be considered as suspended material. The addition of sediment to water causes an increase in the viscosity of the fluid, although a considerable quantity can be added without appreciably changing the viscosity. Just how much can be added before high viscosities are set up, no doubt, depends on a number of factors, such as particle shape and size. Todd and Eliassen (Proceedings, American Society of Civil Engineers, December 1938, p. 1950) found that loess in water became plastic when the loess weight became 56 to 58 per cent of the total of the fluid.

In the attached table are given a number of records of unusually high

TABLE 1. *High sediment concentrations of some streams*

River	Location	Per cent by by Weight	Authority	Reference and Remarks
		RIVERS OF THE UNITED STATES		
San Juan	Goodridge, Utah	40.8	Howard and Love	(1)
Rio Puerco	Rio Puerco, N. M.	52.3	Yeo	(2)
Bad	South Dakota	10	Straub	(3)
Rio Grande	San Marcial, N. M.	21.36	Follansbee and Dean	(4)
Colorado	Grand Canyon, Ariz.	14.4	Howard	(14)
		CHINESE RIVERS		
Yellow	Sanchow-Honan	39	Eliassen	(5)
Lo		50	Todd	(6)
Yung Ting		55.7		(7)
Ching	Shensi	51	Eliassen	(5)
Fen	Shansi	23.1	Todd	(8)
San Chuan		30+	Eliassen	(9)
Upper Tang		6.9	Eliassen	(10)
Upper To		7.2	Eliassen	(11)
Yeh		9.0	Eliassen	(11)
Chang		9.8	Eliassen	(12)
Hu		9.1		(7)
Wei		41.3		(7)
		SOUTH AFRICAN RIVERS		
Great Fish	Craddock	9.87	Warren	(13)
Wlekport River		11.24	Warren	(13)

sediment concentrations actually observed in streams. These records show that the percentages in some cases reach as high as 50 per cent in natural rivers. There is good reason to believe that the sediment, in the case of these high concentrations, is very fine. In most cases these figures represent the average concentration in a river in a given time, but, in some instances, they may represent the concentration of a single sample. Only the highest value in each river has been recorded, but, in the case of many of the rivers, more records of very high concentration have been observed.

When streams carry very high concentrations, their appearance is changed. In describing the flow of the San Juan River Pierce states: "When a river carries a very high sediment load it has a smooth, oily movement, as a stream of molten metal, instead of the usual rough, choppy surface" (U.S. Water Supply Paper No. 400, page 41). Eliassen has observed a similar condition. He states: "When a river gets more than five per cent of silt by weight, all eddy currents become damped, and water flows in a straight line motion one never sees when the water is clear" (private communication). During these heavy sediment flows, the fish swim around near the surface and are easily caught. It is not known whether it is because they need air or because they are unable to submerge themselves in the higher specific gravity water.

REFERENCES

1. Eng. News-Record, Oct., *1930*, pp. *621*.
2. Report on Silt in Four Floods in the Rio Puerco Watershed, *1938*, H. W. Yeo, Soil Conservation Service. Single sample taken at a drop, Sept. 2, 1938.
3. Missouri River, 73rd Cong., 2nd Session, House Doc. 238, p. 1063.
4. Water Resources of the Rio Grande Basin, *1888–1913*, Follansbee and Dean, U.S.G.S. Water Supply Paper 358, p. 712.
5. Journal of the Assoc. of Chinese and American Engineers, *1934*, vol. 15, 26 and 29. Often above 30, would stay above 30 for several days.
6. *Journal of the Assoc. of Chinese and American Engineers, 1937, vol. 18, 388. A single* sample in 1934 gave 63 per cent.
7. Data from Tables of Stage-Discharge and Sediment Records of Chinese Rivers, *1934*.
8. *Fen Ho Report, 1933*, pl. *26*.
9. Journal of the Assoc. of Chinese and American Engineers, *1936*, vol. 17, p. 35.
10. Journal of the Assoc. of Chinese and American Engineers, *1936*, vol. 17, p. 383.
11. Journal of the Assoc. of Chinese and American Engineers, *1937*, vol. 18, p. 40.
12. Journal of the Assoc. of Chinese and American Engineers, *1937*, vol. 18, p. 51.
13. South African Irrigation Magazine, *1922*, vol. 1.
14. Suspended Matter in the Colorado River in 1925–28. C. S. Howard, U. S. Geological Survey Water Supply Paper, No. 636, p. 32.

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RALPH DANIEL REED

The passing of Dr. Ralph Daniel Reed at Pasadena on January 29, 1940, terminated the career of a remarkably capable geologist and a man of the finest personal traits of character. Dr. Reed left a monument of scientific contributions, made during his all too brief period of literary productivity, many of which are of value to the student of sedimentation.

Dr. Reed was born on April 21, 1889 at Democracy, Ohio. In 1913 he received the degree of Bachelor of Science from Hiram College, Ohio, and after a varied career of teaching in high schools (he became principal of the high school at Orrville, Ohio) he studied geology at Ohio State University and later at the University of Illinois. In 1922 he entered Stanford University where he had secured a teaching fellowship, and eventually he secured his degree of Doctor of Philosophy from that institution. As geologist with the Coast Land Company, as chief geologist of its successor, the Marland Oil Company, and last, as chief geologist of The Texas Company (California), he continued his study of geology and acquired that extensive knowledge of the geology of California which lead to the two scholarly books on that field published by the American Association of Petroleum Geologists.

It is not intended here to write a biography of Ralph D. Reed nor to list all his many important scientific articles. Biographical facts can be obtained from the article "Ralph Daniel Reed, Honorary Member," by H. W. Hoots and C. R. McCollum, in the American Association of Petroleum Geologists Bulletin for December 1939 (vol. 23, no. 12, pp. 1884–1887). A list of his papers can be secured from the available bibliographies. It is intended here to call to the attention of students of sedimentation those papers by Dr. Reed which have the most direct bearing on their particular field. Ralph Reed was exceptionally capable at synthesizing scattered facts and many of his papers drew upon sedimentary data for aid in interpretations of structural relations and paleogeography. Some of these, perhaps, have been inadvertently omitted from the list given below. His many critical reviews of the works of others, some of them of much value to students of sedimentation, are not listed since they are very numerous and nearly all are available in the Bulletins of the American Association of Petroleum Geologists.

"Role of heavy minerals in the Coalinga Tertiary formations." Economic Geology, Vol. 19, pp. 730–749, 2 figs., 1924.

"Miocene paleogeography in the central Coast Ranges, California." Amer. Assn. Petrol. Geol. Bull., Vol. 10, pp. 130–137, 1 fig., Feb. 1926.

"Aragonite concretions from the Kettleman Hills, California." Jour. Geol., Vol. 34, no. 8, pp. 829–833, 2 figs., 1926.

"Sand-calcite crystals from Monterey County, California." Amer. Mineralogists, Vol. 11, no. 2, Feb. 1926. Occurrence by R. D. Reed, with references to literature on other occurrences. Crystallography by Austin F. Rogers.

"Wind and soil in the Gabilan Mesa." Jour. Geol., Vol. 35, no. 1, pp. 84–88, 1 fig., 1927.

"Subsurface correlations by means of heavy minerals." Amer. Assn. Petrol. Geol. Bull., Vol. 11, no. 4, pp. 359–368, 4 figs., April 1927.

"A siliceous shale formation from Southern California." Jour. Geol., Vol. 36, no. 4, pp. 342–361, 4 figs., May–June 1928.

"The occurrence of feldspar in California sandstone." Amer. Assn. Petrol. Geol. Bull., Vol. 12, no. 10, pp. 1023–1024, October 1928.

"Sespe formation, California." Amer. Assn. Petrol. Geol. Bull., Vol. 13, no. 5, pp. 489–507, May 1929.

"Recent sands of California." Jour. Geol.,

Vol. 38, no. 3, pp. 223–245, 15 figs., 1 table, April–May 1930.

"Microscopic subsurface work in oil fields of United States." Amer. Assn. Petrol. Geol. Bull., Vol. 15, no. 7, pp. 731–754, July 1931.

"Geology of California." Amer. Assn. Petrol. Geol., 1933. xxiv+355 pp., 60 figs., 1933.

"Sedimentation und faltung im südlichen Kalifornien." Stille-Festschrift, pp. 232–233, 1936. Co-author with J. S. Hollister and H. Ashauer.

"Structural Evolution of Southern California." Amer. Assn. Petrol. Geol. Bull., Vol. 20, no. 12, pp. 1529–1704, 57 figs., 9 pls., 6 tables, 1 tectonic map, December 1936. Separately published, 157 pp., 57 figs., 9 pls., 6 tables, 1 tectonic map, 1936.

A number of abstracts of papers presented by Dr. Reed at scientific meetings have been published, some of which contain valuable data in brief form but are not included above.

Sedimentary petrology has lost a scholarly coworker in the death of Dr. Reed. May the high quality of his work and the breadth of his correlations of separate data be an inspiration to those who continue the advance of geologic knowledge.

U. S. GRANT, IV,

Univ. California,
Los Angeles, California

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MEMORIAL TO PROFESSOR W. A. TARR

The passing of W. A. Tarr of the Department of Geology of the University of Missouri on July 28, 1939, removed from the ranks of geologists one of its most kindly teachers as well as a fearless investigator and splendid gentleman.

Professor Tarr was born in New Cambria, Missouri, on March 29, 1881, and he was a little more than 58 years of age at the time of his death. He received the degree of Bachelor of Science from Oklahoma A. & M. College in 1904, the degree of Bachelor of Science in Mining Engineering from the University of Arizona in 1908, and the degree of Doctor of Philosophy from the University of Chicago in 1916. He began his work in Missouri in 1911 and was made a Professor in 1919. He held this position at the time of his death.

Professor Tarr was interested in sedimentary problems for more than a quarter of a century, particularly those connected with origins of chert (flint), concretions, and cone-in-cone. He was largely responsible for several topics in the Treatise on Sedimentation. He became a member of the Committee on Sedimentation about twenty years ago and was a member at the time of his death. Before he became seriously ill he had assumed responsible work on the committee and was a contributor to its annual reports. He was always willing to assume responsibilities; what is more to the point, he attempted to bring to completion whatever he undertook. Professor Tarr became editor of the "Compass," the national journal of Gamma Epsilon in 1920, and was its editor until his death. Editorial work connected with the 19th volume was done on his sick bed. He brought this journal from a humble beginning to its present standard and made it unique among fraternity journals in that it contains important scientific articles.

Professor Tarr's last year was spent for the most part in bed. It was not a comfortable year; the disease was cancer and he never seems to have known that he was doomed. A letter received from him on April 19, 1939 about three months before his death, stated that he was slowly gaining. He taught his classes during the college year of 1938–1939 from his sick bed and through all his pain and suffering he is said to have maintained the same cheerfulness and optimism which we who knew him had long learned to know as among his most striking characteristics. Helpful, kindly, enthusiastic, optimistic, he lived, and thus he passed away.

W. A. TWENHOFEL,
University of Wisconsin, Madison, Wisconsin

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NEW GEOLOGY GEOPHYSICS BUILDING AT THE COLORADO SCHOOL OF MINES

The recently completed Geology-Geophysics building of the Colorado School of Mines was dedicated on March 15, 1940 as the last event of Engineers' Day. Dr. E. L. DeGolyer of Dallas, Texas gave the dedicatory address in which he surveyed the development of geology and geophysics and called attention to the present applications of these two sciences. The new building has been named Berthoud Hall after Captain E. L. Berthoud, first professor of geology in the Colorado School of Mines.

The building has three main floors, an upper fourth floor for storage, a basement, and is completely air-conditioned and modern in every respect. It comprises a main section which houses the department of geology and two large wings in one of which is the department of geophysics and in the other the college museum. The building and equipment represents a cost of about one-half million dollars.

The museum contains the School of Mines collection of minerals and fossils Noteworthy among the fossils is a collection of crinoids recently donated by Mrs. John T. Barnett of Denver. Murals in the museum were painted by Irwin D. Hoffman for Treasure Mountain at the Golden Gate International Exposition and were procured for the School of Mines by Mr. and Mrs. Barney Lee Whatley of Denver.

Technical sessions were held during the morning of Engineers' Day and papers on geology, geophysics, petroleum mining and metallurgy were read by men prominent in the mineral industry.

Following the dedication program, Dr. Francis M. Van Tuyl, chairman of the department of geology, Dr. C. A. Heiland, chairman of the department of geophysics and Dr. J. Harlan Johnson, curator of the museum and members of the various staffs held open house for guests of the college who had come to attend the dedicatory services and to view the new college building.